Volume 16 Number 9

BULLETIN
of the
AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

SEPTEMBER 1932

Symposium on Reservoir Conditions in Oil and Gas Pools

INTRODUCTION

In former days, not many years ago, geologists concentrated most of their attention on the search for geologic structure that might contain oil, and their search was confined very largely to surface mapping; and operators concentrated most of their attention on drilling down to the expected pay formation as rapidly as possible. In the last decade, however, we have witnessed not only a remarkable diversification, but also a remarkable improvement, in the technique both of geological exploration and of methods of exploitation. Two of the most noteworthy advances in recent years have been, first, a general recognition of the fact that the gas-oil ratio (the quantity of gas produced with a barrel of oil) has relatively narrow economic limits within a given field, and second, the almost universal acceptance of the fact that straight-hole drilling — less speed with more care — is good practice, scientifically and economically.

We are now in a period of further readjustment, a period in which the principle of systematic pool operation is winning ever widening approval. We admit that an oil pool is a single body, with fairly definite boundaries, and we admit that within a pool there are certain fluid and energy relations which are more or less disturbed by drilling at any point into the pool. What one operator does in drilling and producing his well may have an important effect on the oil and gas, and on the rights and privileges, of other owners in the pool. Thus, the consensus of opinion within the industry is more and more in favor of exploiting a pool by some method of scientific, orderly development, with fair participation in the

oil and gas by all owners of the pool, and with efficient utilization of the natural energy of the pool for lifting the oil to the surface. We are moving forward toward more rationalism and greater stability in our methods of producing petroleum.

In this progress toward increased efficiency in exploitation and greater conservation of this valuable natural resource, petroleum engineers are constantly in need of geological data pertaining to conditions actually existing in the reservoir. Problems of well spacing, proper sand penetration, best methods of finishing wells in the "pay," most effective kind of tubing, most satisfactory daily field production allowable, most efficient rate of production for each well, and so on — these are all engineering problems which, for their study and solution, require a knowledge of geological factors such as the kind of reservoir rock, the type of geological structure involved, the porosity and permeability of the pay rock, the distribution of variations in the lithology and stratigraphy of the pay rock, the nature and distribution of energy within the pool, the relations of bottom water and edge water to the oil, and the relative amount of gas within the reservoir. These geological data are of primary importance not only for guiding current operations in a field, but also for planning the future drilling program along lines of equitable sharing and reasonable conservation. In the group of papers which follows, several of the topics here listed are discussed. These papers are not offered as a comprehensive treatise on the subject, but rather as an introduction to the study of reservoir conditions. All contain much food for thought.

J. G. Bartram describes the variations in porosity and permeability of the several sandstones and limestones which yield oil or gas in Colorado and Wyoming, and he shows how these differences affect production and water encroachment.

D. R. Snow, in his paper, dwells on the subject of water encroachment in the Bartlesville sand, more especially in the Nowata area, the Bird Creek pools, the Burbank pool, and the Glenn pool. He compares the conditions in these Bartlesville sand pools with those in the East Texas field.

C. V. Millikan discusses reservoir pressures, reservoir energy, and recovery, and explains the importance of measuring bottom-hole pressures to serve as a valuable aid in correlating porous formations, determining reservoir conditions, choosing efficient well spacing, planning rate of development, estimating reserves, et cetera.

E. V. Foran outlines the history of changes in bottom-hole pressures in the East Texas Field, before and after the military shut-down, and he shows how these data have been interpreted and put to practical use.

In the paper by Brankstone, Gealy, and Smith, the authors describe the technique of the laboratory determination of densities and porosities of rock samples.

C. M. Nevin, in his contribution, published in this *Bulletin* last April, emphasizes the importance of ascertaining the permeability of reservoir rocks, and shows how he determines the permeability of rock samples in the laboratory.

The article by J. Versluys is of a more theoretical nature than the others herewith included. It relates especially to differences in texture, porosity, and permeability of strata, in their relations to water circulation and oil and gas accumulation in the gradual building of an oil pool. The reader should clearly understand that many of the statements in this paper refer to very slow movement of fluids during long geologic ages, rather than to the much more rapid changes induced in an oil pool, already formed, after it has been tapped by drilling.

Perusal of these papers will bring out one obvious conclusion, that no general rules can be formulated to cover the conditions existing in all pools, or indeed even in the reservoir rock in different parts of the same pool. Each field must be studied as it is developed. Data must be collected as the wells are drilled, and as these data are thus accumulated, their analysis will indicate what course to pursue for attainment of highest efficiency in operating the pool.

With the exception of geologic structure and kind of reservoir rock, very little attention was paid, ten or twelve years ago, to these other geologic conditions of porosity, permeability, detailed lithology, and reservoir energy. It behooves us geologists to realize this expansion in our field of service to the industry and to bend our energies toward learning all we can of these geologic factors which together constitute the necessary foundation of modern engineering in the production of oil and gas.

FREDERIC H. LAHEE

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 9 (SEPTEMBER, 1932), PP. 864-880, 11 FIGS.

CHARACTER OF PRODUCING SANDSTONES AND LIMESTONES OF WYOMING AND MONTANA[1]

JOHN G. BARTRAM[2]
Denver, Colorado

ABSTRACT

Oil and gas are produced in Wyoming and Montana from a wider range of beds in the geologic section than in any other district in the United States, as commercial fields have been developed in Mississippian, Pennsylvanian, Permian (?), Jurassic, Lower Cretaceous, Upper Cretaceous, and Eocene formations. As this area received Pennsylvanian and Permian sediments from the Wichita uplift of Colorado, New Mexico, Texas, and Oklahoma; early Jurassic sediments from an uplift on the southwest; late Jurassic, Lower Cretaceous, and Upper Cretaceous sediments from the Cordilleran uplift of the Great Basin area on the west; and Eocene sediments from the Rocky Mountain uplift, it is evident that the origin and character of the beds vary greatly. The purpose of the writer is to describe the characteristics of the different producing sandstones and limestones and to make available information that may help solve the modern production problems of unit operation, well spacing, repressuring, and the like. All of these formations have different characteristics and each must be drilled and operated in a separate manner, even though several may produce on the same anticline.

INTRODUCTION

The northern Rocky Mountain area is an exceptional oil province, because oil and gas are produced from so many different formations scattered through a wide range of geologic time. Commercial production is found in beds of Mississippian, Pennsylvanian, Permian (?), Jurassic, Lower Cretaceous, Upper Cretaceous, and Eocene age, and one occurrence is possibly in the Ordovician. The character of the rocks in these different groups varies widely, because at least three and probably four major uplifted areas have supplied sediments to the Wyoming formations, and from different directions.

Figure 1 shows the position of three of these major uplifted areas and the small black dots are the principal oil fields. The Pennsylvanian and Permian sediments were largely eroded from the land masses in Colorado that were the northwest end of the Wichita Mountains uplifted in Mississippian and Pennsylvanian time and extending from southern Oklahoma to the south boundary of Wyoming. The basal

[1]Read before the Association at Oklahoma City meeting, March 25, 1932. Manuscript received, March 26, 1932.

[2]Geologist, Midwest Refining Company.

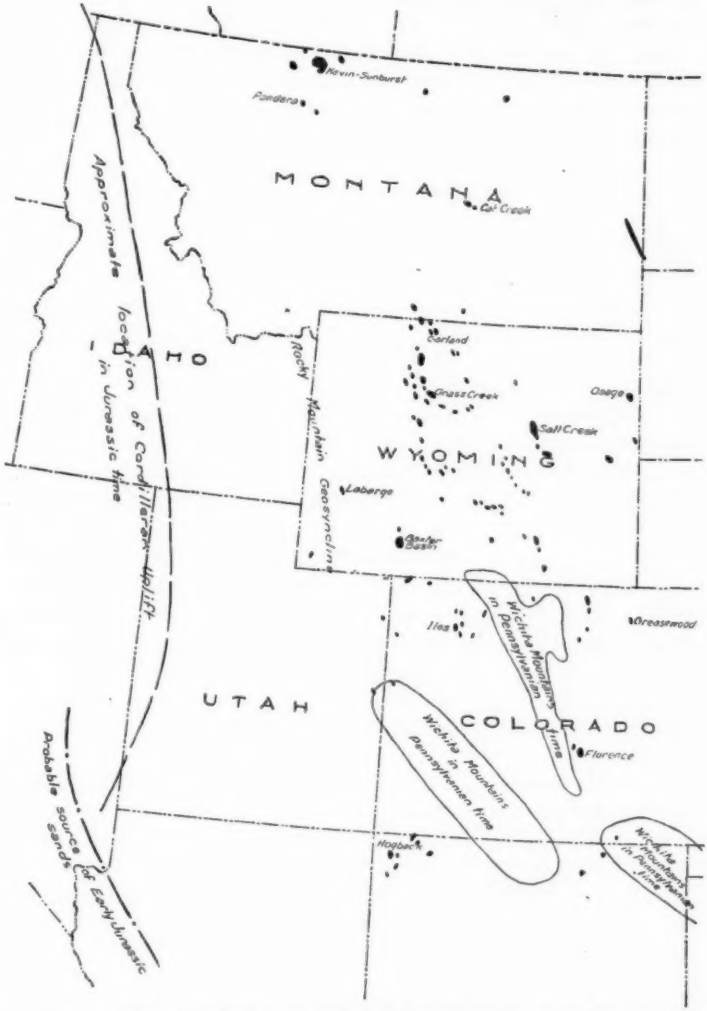

FIG. 1.—Map of Rocky Mountain states showing location of principal oil fields and of principal uplifted areas that supplied sediments.

Jurassic sands must have come from an important uplifted area on the southwest and west in Arizona and Nevada. The later Jurassic, Lower Cretaceous, and Upper Cretaceous rocks were derived from the Cordilleran uplift of the Great Basin area in Utah, Nevada, and Idaho. Sediments from that great range of mountains were washed into the Rocky Mountain geosyncline, which sank as a deep trough. In late Upper Cretaceous or early Eocene time, when the Cordilleran chain was worn down and deeply eroded, the geosyncline was itself folded and faulted to form the present Rocky Mountains, and from these last came the Eocene deposits.

At Salt Creek the methods used for the Upper Cretaceous sands are unsuitable for the Lower Cretaceous, Jurassic, or Pennsylvanian beds, and each has its own problems. To picture adequately the character of these reservoir rocks it is necessary to describe the geologic history of their deposition.

The generalized geologic section (Fig. 2) is complete for central Wyoming except that some Tertiary beds are omitted at the top. They do not produce oil in that part of the state, but do contain oil in western Wyoming, where the remainder of the geologic section is considerably different.

PRODUCING FORMATIONS

On the basal granite is the Cambrian Deadwood formation, which has been properly tested in only a few localities but which has yielded no oil or gas. Next is the Ordovician Bighorn limestone, probably equivalent in part to the Viola limestone of Oklahoma. No oil has yet been found in it, unless it be in the bottom of a deep well in the Garland field of northern Wyoming, but that well is probably still in the Mississippian.

The Madison limestone, Tensleep sandstone, and Embar limestone of Mississippian, Pennsylvanian, and supposedly Permian age are the so-called black oil horizons of Wyoming and produce asphaltic oil of 16°-35° A. P. I. gravity in many fields, with an average gravity of 22°-25° A. P. I. The Triassic red beds are almost barren of oil, but above them are the light oil sands in the Sundance formation of Jurassic age, in the Dakota group of the Lower Cretaceous and base of the Upper Cretaceous, and the Wall Creek or Frontier sands higher in the Upper Cretaceous. Still farther up in the column is the Shannon sand, and in a few scattered fields gas and a little oil have been found in sands high in the Upper Cretaceous, and even the Tertiary.

To date, most of the oil produced in Wyoming has come from the Wall Creek sands and the Dakota group is next. In the future more

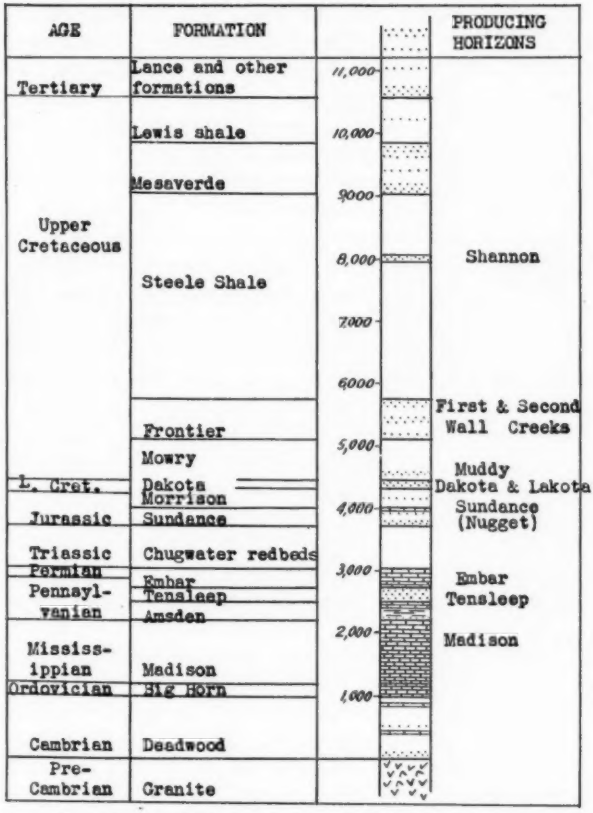

FIG. 2.—Generalized geologic section in central Wyoming. Tertiary formations are omitted at top. Thickness above pre-Cambrian, shown in feet.

black oil will be produced from the Embar and Tensleep and many fields now closed will be opened, as the supply of light oil decreases.

Madison limestone.—The Madison limestone of Mississippian age is the lowest commercial oil horizon in Wyoming and Montana. It is a hard, massive limestone series, ranging from 600 to 1,500 feet in thickness, forming prominent outcrops in the mountains. It was deposited in almost the entire Rocky Mountain area, and until recently was regarded as a uniform limestone, but more careful study and the results of recent drilling show surprising variations that have not yet been fully explained.

Oil has been found in the Madison limestone under two different sets of conditions. In northern Montana there is production in the weathered top of the formation beneath an unconformity, but apparently not much porosity exists lower in the limestone. At least, no oil has been found below the top. Three hundred miles farther south, in northern Wyoming, where no large unconformity exists at the top of the Madison limestone, there are many porous dolomites scattered throughout at least the top 600-800 feet of the formation.

In the Kevin-Sunburst field in northern Montana, Jurassic marine shales rest on weathered, rotten Madison limestone, and oil that originated in the Jurassic is produced from cavernous openings in the top few feet of the limestone. Deep wells that penetrated all the formation found water in some porous horizons below the top, but most of it seems to be tight. In the near-by Pondera field, conditions are the same except that the producing layer at the top of the Madison is a fine-grained granular dolomite that grades downward into white limestone that is non-porous and barren. No large cavernous openings were found and there were no very large wells. A small amount of water comes with much of the oil, but there is not a heavy hydrostatic head of water behind the oil, probably because the porosity is not continuous for any distance.

In the Garland or Byron field of northern Wyoming, three wells have developed gas and oil throughout a thickness of 600-800 feet of the Madison limestone. There may be a slight unconformity at the top of the limestone, but it can not be large, because Pennsylvanian beds rest on the Mississippian. Porosity is found in the top of the Madison, but it also continues down through the entire formation. Rotary cores reveal an alternating series of porous and non-porous dolomites and limestones. The producing horizons are fine-grained dolomites, very porous because of holes as large as a pin-head or larger. Free oil fills these pores and the dolomite is also completely saturated between the crystal faces. These latter openings are so small that much of this oil may never drain out.

These and other differences in the character and production of the Madison limestone have not been satisfactorily explained and the formation presents interesting problems for the future. As an example of such a problem, at Casper and Salt Creek the Madison "limestone" consists mostly of sandstone, which suggests a near-by shore line. Johnson[1] has recently concluded from his work in central Colorado that there was a small Colorado land mass in Mississippian time. It is probable that sediments from it were carried north and northeast into Wyoming.

[1] J. Harlan Johnson, unpublished manuscript.

Tensleep sandstone.—The Madison limestone in Wyoming is overlain by the Amsden formation of Pennsylvanian age and that is followed by the Tensleep sandstone, also marine Pennsylvanian. The Amsden yields little oil because of a lack of porous beds, but the Tensleep is a major producer of black oil.

FIG. 3.—Tensleep sandstone, Madison limestone, and other formations in canyon of North Platte River near Pathfinder, southwest of Casper, Wyoming: *t*, Tensleep sandstone; *ra*, Amsden; *m*, Madison. Deadwood at river bed. Reprinted with permission of the director, *U. S. Geol. Survey Prof. Paper 149* (1927), Pl. 12.

It is a uniform body of sand, ranging from 100 to 400 feet in thickness, spread over much of Wyoming. Most of its materials were derived from the land masses in Colorado that were the northwestern end of the Wichita Mountains (Fig. 1), but some materials probably came from a western source. Near the south shore line of the Tensleep sea the materials are coarser and redder, but in most of its area it is practically pure sand containing almost no shale. In some localities it may have in it a few dolomites, limestones, or sandy limestones. It is extensively cross-bedded but very regular in thickness.

The variations in the production of the Tensleep sandstone are due to great differences in the amount of cementing materials between the grains rather than to variations in the size or shape of the grains themselves. The bed is not all porous and saturated in the oil fields, but may contain considerable thicknesses of tightly cemented barren sandstone

at irregular places. The drillers have not recognized this condition, and usually log it all as good oil sand, and for this reason many estimates of future production from the Tensleep are too high. This irregular cementation prevents the oil and water from separating on a uniform water table and causes freakish occurrences of water high on a fold and of oil far below the water level of other wells in a field.

The Tensleep sandstone is a good water carrier and in much of Wyoming produces flowing water where barren of oil. It should furnish a water drive to many of the black oil fields, but if the sand is too irregularly cemented in a field, it may leave much oil in the sand.

Embar limestone.—The Embar limestone that rests on the Tensleep sand is equally important as a producer of black oil, but is reservoir rock of a different type. The oil occurs in porous dolomites, chert beds, and in a few places in thin sandstone. The formation itself contains numerous chert horizons and beds of phosphate rock and has been generally believed to be of Permian age, although several paleontologists report Pennsylvanian faunas from its lower half. The widespread notion is that 200-300 feet of Embar limestone contains several important producing horizons, and that most of it is saturated and will produce oil. Geologists wishing to prove that the porosity in the limestone was caused by an unconformity have quoted references to an unconformity at the top of the Embar, but the writer has not been convinced that one is present there.

Detailed study of these beds shows that several of the ideas stated in the preceding paragraph are not correct, and that the facts about the Embar have not been understood.

Figure 4 shows partial logs of representative wells in several Embar oil fields. The solid black areas indicate the position of porous beds, and the regular limestone symbol shows dry limestone. From this it is evident that there is no porosity at the top of the Embar formation of central and north-central Wyoming, and that in every field there is 25-125 feet of dry barren limestone overlying the oil or water reservoir.

Figure 5 shows a measured section and an accurate sample log of a producing well in the Grass Creek field. At the top beneath the Triassic red beds are the Dinwoody gypsiferous shales that were formerly included in the Embar, but were made a separate formation when the fauna suggested Triassic age. Next is the barren limestone, which in many places is green and in some places contains glauconite. Beneath it on the outcrop are coarse chert beds in a matrix of shaly limestone, dolomite, and calcareous shale.

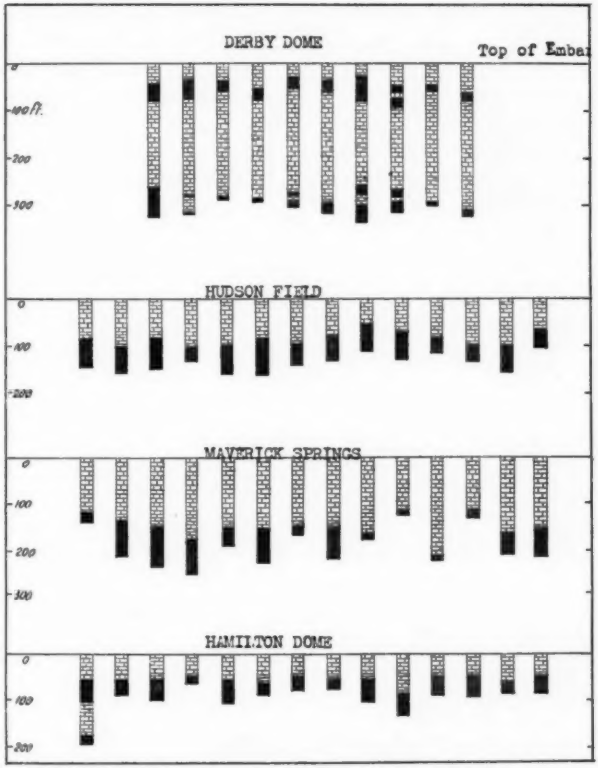

FIG. 4.—Dry barren limestone in top of Embar formation in several Wyoming fields. Solid black indicates saturation or porosity.

In the Embar fields the first and best oil in the formation is found in the highest cherty horizon. The presence of this porosity, as well as chert and phosphate beds, is good evidence that an unconformity is present in the Embar, but it is not at the top, as formerly believed.

The writer now suggests that parts of two separate formations have been wrongly included together in the Embar of the oil companies, and that beneath the unconformity the beds are probably Pennsylvanian in age and above it they are Permian and might be closely related to the Dinwoody. The United States Geological Survey first included in the Embar limestone[1] all the beds from the top of the Dinwoody to the top

[1]N. H. Darton, "Geology of the Bighorn Mountains," *U. S. Geol. Survey Prof. Paper 51* (1906), p. 35.

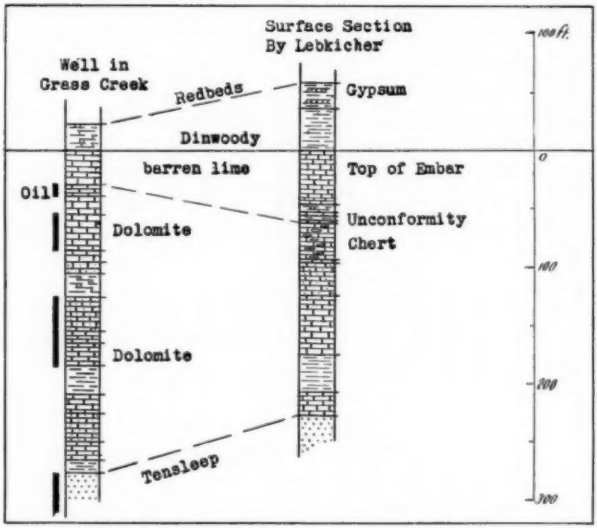

FIG. 5.—Character of Embar formation in Grass Creek field and vicinity.

FIG. 6.—Outcrop of top of Embar limestone in Shoshone Canyon near Cody, Wyoming, showing barren limestone at top, and, beneath black line, cherty porous beds.

of the Tensleep, but when the Dinwoody was shown to be probably Triassic[1] it was separated and the remainder called first Park City and then the Phosphoria formation. The latter name was used after the Park City had been proved at its type locality to be partly Permian and partly Pennsylvanian.[2] The writer now believes that the Phosphoria, which is now the same as the oil geologist's Embar, should be divided and the unconformity recognized. It is interesting that Girty[3] states "The fauna of the upper member of the Phosphoria formation, . . . , differs strikingly from the fauna of the phosphatic shales." Condit also states that Girty considers the fauna from the lower part of the Phosphoria to be Pennsylvanian. As the nomenclature of the Embar group is already confused, the writer is not suggesting a change of names, at least until additional work has been done.

In Figure 5 the solid black lines at the side of the well log indicate the location of porosity and oil saturation in the formation. The upper porosity is ordinarily the best and the writer believes a very large percentage of the Embar oil comes from the first 10-20 feet beneath the unconformity. The producing horizon may be porous, granular dolomite, coarse chert with a matrix of shaly limestone, or fairly loose residual sandstone. Lower in the Embar some porous dolomites or sandy limestones occur and yield some oil or water, as in the well shown, but they are probably not commercially important, and the writer can not agree with those who say the formation has several valuable productive horizons. In the lower part the limestones are dense and tight and there is much more shale.

Jurassic sandstones.—Above the Embar limestone and Dinwoody shales are the Chugwater red beds of Triassic age, 500-800 feet of bright red sandy shale, red sandstone, and some gypsum. These fine-grained red sediments were spread out evenly over a large area in the Rocky Mountains, and the writer thinks they came from the south and southeast, perhaps from the Ouachita uplift of Texas.

At the end of Triassic time, conditions began to change completely in the Rocky Mountain district. The Colorado land masses that had risen with the Wichita Mountain uplift had been worn away or covered, and new land masses were rising in the southwest and west, and different sediments began to appear from those directions (Fig. 1). This change

[1]Eliot Blackwelder, "New Geological Formations in Western Wyoming," *Washington Acad. Sci. Jour.*, Vol. 8 (1918), pp. 417-26.

[2]G. R. Mansfield, "Geography, Geology and Mineral Resources of Part of Southeastern Idaho," *U. S. Geol. Survey Prof. Paper 152* (1927), p. 78.

[3]G. H. Girty, *U. S. Geol. Survey Prof. Paper 152* (1927), p. 79.

began with the deposition of a tremendous mass of pure sandstone, thickest in northern Arizona and southern Utah where the Navajo and Wingate sandstones are more than 2,000 feet thick. This sand body continued into western Wyoming as the Nugget sandstone, but tapered out in an even but thinning sheet toward the north, northeast, and east. No one has really shown where this sand came from, but probably the first great uplift of the Cordilleran folding occurred somewhere near western Arizona and Nevada and extended some distance north.

The sands eroded from this land mass were spread as a sheet over at least the southern two-thirds of Wyoming and extended east to the Black

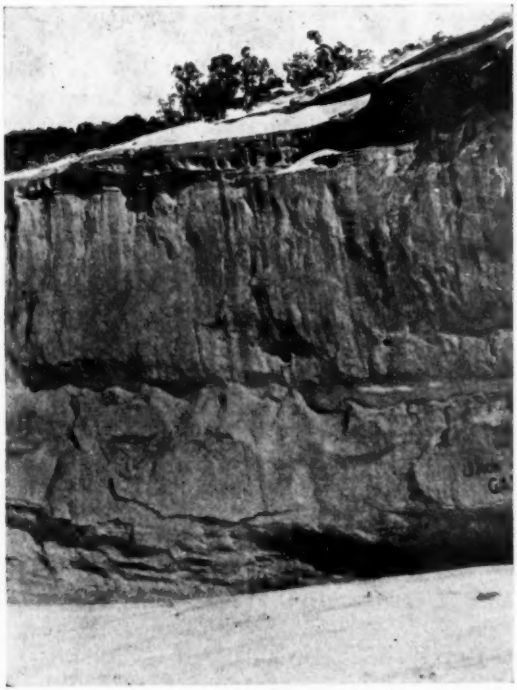

FIG. 7.—Outcrop of basal Sundance sandstone near Casper, Wyoming.

Hills of South Dakota, and were the basal sands of an invading, shallow Jurassic sea. All the marine Jurassic beds, including the basal sand, are known as the Sundance formation in central and eastern Wyoming.

There are other less important oil sands in the 300-400 feet of the formation, but the Sundance sand is usually considered the basal bed. It is known also as the Nugget sandstone.

Its outstanding characteristics are the purity of the sand and the lack of bedding planes or partings of any nature. It is extensively cross-bedded and ordinarily soft, although in places, as in part of the Lost Soldier district, it may be tightly cemented and low in porosity. Under the microscope it is easily recognized by a peculiarly etched or frosted appearance of the sand grains and by the even manner in which they are rounded. In fact, the Sundance sand has more even, regular porosity than any other producing horizon in Wyoming and can be considered a true sheet sand.

There is ordinarily strong water pressure in the Sundance and at Salt Creek and other fields the water should ultimately wash all the oil into the highest wells on the anticline.

Dakota group of sandstones.—Later in Jurassic time the western uplift (Fig. 1) continued to develop and extended northward through western Idaho far into Canada. As the great Cordilleran range or ranges came up, the land on the east sank somewhat and the Jurassic sea moved in. It was a relatively shallow sea and was filled soon with sediments from the Cordilleran land on the west in parts of Utah, Nevada, Idaho, and some adjacent states. This new land mass rose slowly at first or at least was eroded slowly and shale and other fine sediments spread over the Rocky Mountain states in great even flood plains to form the Morrison formation, which contains few important sandstones and little production.

At about the close of Lower Cretaceous time, erosion increased for a while on the Cordilleran uplift, coarser sediments were swept eastward, and the Rocky Mountain area again settled enough to permit the invasion of the Upper Cretaceous sea. This combination of events resulted in the deposition of a series of sandstones that are known as the Dakota or Cloverly group, various members of which are named the Lakota, Dakota, Muddy, Greybull, Cat Creek, and Sunburst sands. They are very important producers of oil and gas in the mountain states.

Although the Dakota and Lakota sands are so irregular and lenticular that their thickness and character can not be predicted accurately from well to well in the same field, we have attempted for years to correlate them in detail throughout hundreds of miles, and with a fair degree of success. In central, eastern, and southern Wyoming and in northern Colorado, where three sands occur in the group, they are known

FIG. 8.—Outcrop of Muddy, Dakota, and Lakota sandstones along North Platte River near Alcova, Wyoming. Thin Muddy sandstone caps shale hill on skyline. Dakota and Lakota sands are merged together without intervening shale.

as Muddy, Dakota, and Lakota sands. The basal sand, the Lakota, is conglomeratic.

The writer considers the Lakota sand to be probably Lower Cretaceous in age. Above it in most places is a thin bed of light, varicolored or reddish shale, followed by the Dakota sand, which is the basal sand of the Upper Cretaceous sea. It is not as coarse as the underlying Lakota. In many places the intervening shale may be absent and the Dakota and Lakota may be together as one bed, but at other localities there may be several shale partings that divide the beds into three or four sandstones. Above the Dakota is the first black marine shale of the Upper Cretaceous followed by the Muddy sandstone, which, though present in a large area, varies greatly in thickness and porosity. The Greybull sand in the Bighorn Basin, the Cat Creek sands in central Montana, and the Sunburst sand in northwestern Montana all belong at about the same horizon and were deposited under nearly the same conditions.

The three sands, Lakota, Dakota, and Muddy, have one common characteristic: they thicken or thin within short distances; otherwise each has its distinctive features. The Lakota sand is ordinarily coarsely conglomeratic at the bottom (Fig. 9), and at most of its outcrops 2-20 feet at the base is a coarse rubble of chert pebbles. The open texture of this conglomerate makes the Lakota a producer of big wells that have large initial flows and soon are flooded with water. It is the sand that several years ago had a rated shut-in potential of 200,000 barrels a day at Salt Creek, and now makes about 2,300 barrels a day, wide open.

The Dakota sand is more fine-grained and really a better producer of oil, but is extremely lenticular and is not continuous for any great distance. Most people regard the Dakota as a regular sheet sand, that

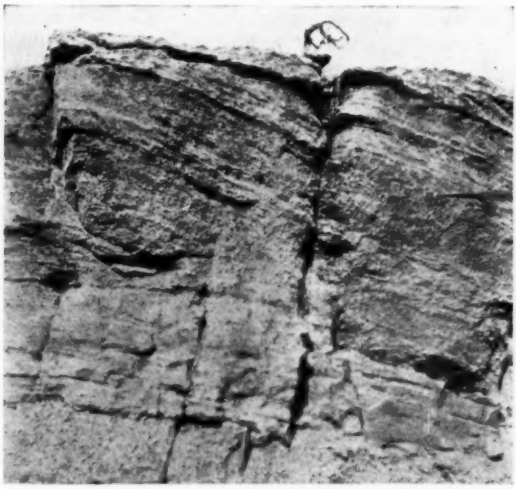

FIG. 9.—Conglomerate in base of Lakota sandstone near Alcova, Wyoming.

is, continuous in the entire Rocky Mountain region. Actually it is a zone of irregular, disconnected lenses at the same horizon.

The Muddy sand is an irregular, fairly thin bed deposited in the lower 100-200 feet of the marine Upper Cretaceous shale. It probably is an eastern tongue of one of the sandstones of the Bear River formation of western Wyoming. It tends to be shaly and fairly tight but that property has probably retained oil in it on several anticlines by preventing water circulation that flushed the oil out of the more porous Dakota and Lakota sands. The Muddy sandstone is close to the Dakota and Lakota in the section, but in most places is more similar to the Wall Creek sands higher in the Upper Cretaceous shale.

Wall Creek sandstones.—After the Dakota group of sands were washed out from the Cordilleran uplift and the Upper Cretaceous sea covered the Rocky Mountains, erosion became less active on the land mass and several hundred feet of black marine shale was deposited with little coarse material. During this interval drainage channels evidently developed in the upland and when sands were again carried eastward into the Cretaceous sea they did not cover the entire area like flood-plain sheets but were concentrated in certain areas and must have been in the form of low deltas. A large and important river must have emptied into the sea near the southwestern corner of Wyoming and the

Frontier formation, which includes the Wall Creek sands farther east, was deposited. The actual shore line and coarse materials were still farther west, but important coal beds show that at times the surface of the delta was above the water in western Wyoming.

In central Wyoming the Frontier or Wall Creek sands were beneath the water and the sediments were finer materials swept out onto the edges of the delta. As the seasons varied or as floods came in the river systems, the character of the material differed, and, as one would expect, the Frontier formation is composed of alternating rather thin layers of sand, sandy shale, and shale. These deposits spread out toward the east, north, and northeast, and probably merged with deltas formed by

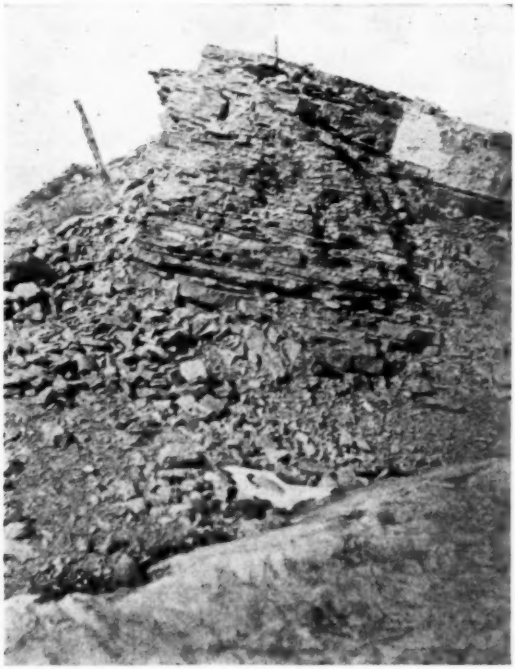

FIG. 10.—Outcrop of First Wall Creek sandstone near Casper, Wyoming. Thin beds and shale partings.

other streams. The Blackleaf sands of northern Montana are in the same position and may be another delta.

Few of the Wall Creek sandstones are clean deposits, free from shale. In the old cable-tool wells, the drillers logged solid sand in considerable thickness, but rotary cores show thin beds of sand parted by layers of shale and sandy shale.

Figure 11 shows a typical core of Wall Creek sandstone, which is surprisingly similar to some cores from the East Texas oil field. There are a few streaks of black chert and coarser material in the Wall Creek sands, but they are generally even and fine-grained with a tendency to be shaly. The porosity is largely controlled by the amount of mud or shale.

The Wall Creek sands are the largest producers of oil in the Rocky Mountains, because they are the principal oil horizons at Salt Creek, the only really large field in the area. Some wells were fairly productive during the early development of a Wall Creek sand field, but the average production is not large and the recoveries per acre are low. The restricted porosity holds back edge water in some places, as in the Second Wall Creek sand at Salt Creek, where the water line has moved almost not at all, but in the more porous First Wall Creek sand, water has worked to the top of the fold, but not in a large flood or drive. In older fields, gas tends to accumulate on the crest of the anticline and the oil to settle down toward the lower edge. Gas drives are fairly successful and increase recovery wherever no very porous layers exist to by-pass the gas. It is interesting that some of these gas drives accelerate the movement of oil down the dip but push little up hill.

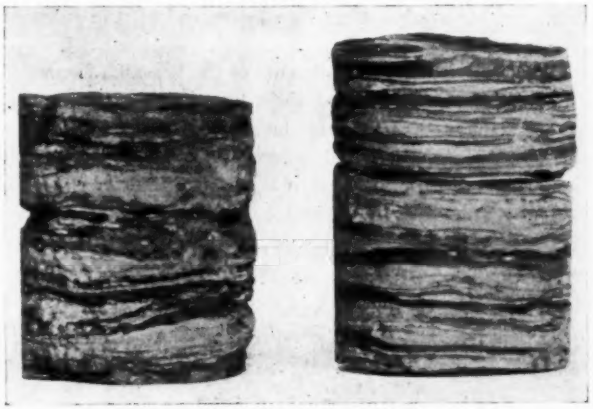

FIG. 11.—Core of Wall Creek sand, Midway dome, near Casper, Wyoming. Typical "broken" sand.

Sandstones above Wall Creek.—The deposition of the Frontier or Wall Creek sands was followed by a long period of quiet, during which 2,000-3,000 feet of marine Upper Cretaceous blue shale was laid down in the Rocky Mountain geosyncline, before another extensive sandstone, known as the Shannon, Eagle, or Virgelle was deposited. The Shannon in central and south Wyoming, the Eagle in central Montana, the Virgelle in northern Montana, and probably also the Blair in southwestern Wyoming are all closely related, if not the same, and represent a great sheet of shaly sandstone swept eastward.

In character these sands are similar to the Wall Creeks, but have not produced much oil, although they do have many gas pools.

As Upper Cretaceous time continued, the Shannon sand was followed by 1,000-2,000 feet of marine dark shale, and then another but much more important wave of sandy materials from the west to form the Mesaverde or Judith River group of sandstones, coals, sandy shales, and shales. The end of the Upper Cretaceous sea was approaching and the shore line was creeping eastward. The Mesaverde sandstones also are unimportant producers of oil.

A final relatively short period of quiet permitted the deposition of 500-1,000 feet of Lewis, Meeteetse, or Bearpaw shale as the last of the marine Upper Cretaceous. Mountain folding increased on the western edge of the Rocky Mountain geosyncline and gradually moved eastward. The sea was entirely filled with coarser sediments and thousands of feet of non-marine Lance and Fort Union rocks accumulated, but no oil has been found in them. The folding continued farther eastward as the present Rocky Mountains came into being and all the sediments described were folded and eroded.

In Eocene time, Tertiary sediments of the Wasatch formation were laid down in another great flood plain unconformably over the truncated edges of older formations in the structural basins. Some oil has been found in these Wasatch beds where they overlie other petroliferous formations, as at Labarge in western Wyoming, and other fields may be found. The character of the Wasatch sands is similar to that of the Dakota and Morrison groups,—irregular, lenticular, fairly coarse sands laid down on a wide flood plain.

DISCUSSION

ED. BLOESCH, Tulsa, Oklahoma: Is the extension of the Wichita Mountains through Colorado a land area only or an extension of the Wichita folding?

J. G. BARTRAM: There is no continuous folded mountain range, but several local mountains. The Fountain formation of the Rocky Mountains is a land deposit of Pennsylvanian age grading into marine sediments toward the east.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 9 (SEPTEMBER, 1932), PP. 881-890, 3 FIGS.

WATER ENCROACHMENT IN BARTLESVILLE SAND POOLS OF NORTHEASTERN OKLAHOMA AND ITS BEARING ON EAST TEXAS RECOVERY PROBLEM[1]

D. R. SNOW[2]
Tulsa, Oklahoma

ABSTRACT

The history of water encroachment in the Bartlesville sand pools of northeastern Oklahoma emphasizes the fact that there has not been any water drive in any of these pools which would help to increase recovery from the sand, either by flushing or by maintaining the reservoir pressure. It is believed that the absence of such water encroachment has caused the ultimate recovery of these sand bodies to be much less than would have resulted under an effective water drive.

INTRODUCTION

The subject of water encroachment in the producing fields of Oklahoma is one that has received very little attention. Water encroachment has commonly been viewed with great alarm; the first appearance of water in any large amount, in a new field, has been considered as marking the beginning of the decline in production and the elimination of that area as a menace to the existing crude price structure. The Bradford, Pennsylvania, water-flooding operations have, of course, proved that water may be of great help in securing additional oil recovery from a sand after the original reservoir pressure has been dissipated. Thus it is evident that water may be a menace or a benefit, according to the conditions under which it enters the sand.

The enormous size of the East Texas producing field and the vital importance of the recovery of oil from that area to the oil industry today, have focused attention on any problem that might shed light on the probable future history of the production from that area, both as to rate and ultimate amount of recoverable oil. Because of the similarity of conditions of the reservoir rocks in East Texas to those of the Bartlesville sand pools of Oklahoma, it is interesting to inquire into the history of water encroachment in these pools and study the effects of such water encroachment on the rate of flow and ultimate recovery of oil.

[1]Read before the Association at the Oklahoma City meeting, March 25, 1932. Manuscript received, March 31, 1932.

[2]Vice-president in charge of geological and land departments, Barnsdall Oil Company.

ACKNOWLEDGMENT

The writer wishes, here, to express his appreciation to E. A. Markley and G. H. Harrington, of the geological department of Barnsdall Oil Company, for their helpful suggestions and assistance in preparing the map and profiles. Grateful acknowledgment is also made to the Tidal Oil Company for permission to use its map showing the distribution of Bartlesville sand in northeastern Oklahoma. This map was originally prepared in the geological department of the Tidal Oil Company under the direction of T. E. Weirich and represents a great amount of work, although much of the detail has been omitted in preparing it for this paper.

BARTLESVILLE SAND

The map (Fig. 1), which includes an area approximately 100 miles from north to south and 115 miles from east to west, shows the areal distribution of the Bartlesville sand in northeastern Oklahoma as it would appear if the overburden were removed. In those areas where well-log

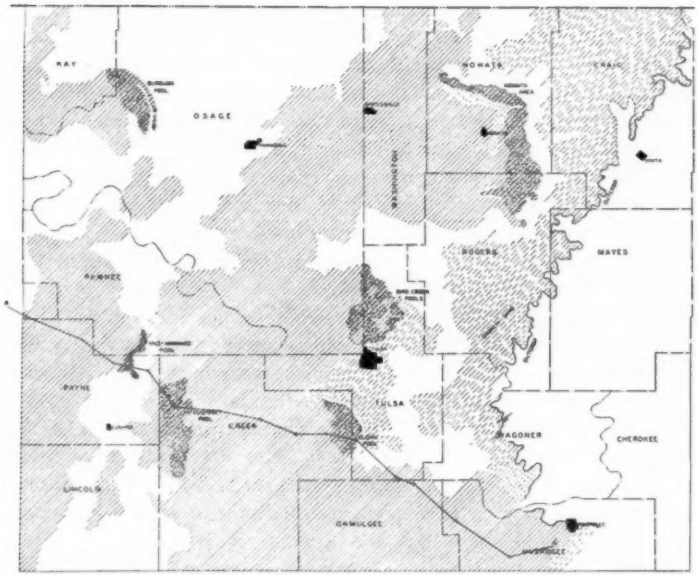

FIG. 1.—Map showing areal distribution of Bartlesville sand in northeastern Oklahoma. *AA'*, line of west-east cross section (Fig. 2). Length of area, approximately 115 miles.

correlations show the sand to be a continuous body, it is represented by continuous lines; where the sand is very thin or broken, by dashed lines; and where absent, by blank spaces. The principal oil-bearing areas are shown by dots between the lines representing the sand. There are many small areas producing from the Bartlesville sand that are not shown on the map.

The Bartlesville is a sand member of the Cherokee shale formation of Pennsylvanian age. It is, in many places, an interfingering of sand and shale, rather than one single member, and though in certain parts of northeastern Oklahoma it can be traced as a sheet or continuous sand body, in other parts it is composed of members which form a sand zone rather than a solid body of sand. The total extent of the Bartlesville sand is much greater than is shown by the map. It is known to extend northward into Kansas, many miles. Toward the south, the sand thickens and is known as "Salt sand" because in nearly every place where penetrated by the drill it contains only salt water. The exact limits on the west are not known, but it is probable that it occurs for many miles basinward in the same relative position in the section.

One of the striking features shown on the map is that the area extending westward several miles from the outcrop, which is known as the Bluejacket sandstone, is an area of broken and shaly sand. This fact is shown by the logs of wells drilled in the area and by the outcrop itself, which in some places is a heavy sand body; in others, nearly pure shale. Continuing westward, there is an area extending from north to south nearly across the entire map where there has apparently never been any deposition of the sand. This irregular area of no sand lying between the outcrop and the main body of the sand offers an opportunity for much speculation as to the exact conditions existing during the time of Bartlesville deposition. It is apparent that this area of no sand or thin sand has formed a barrier to the up-dip migration of oil which resulted in the accumulation of the oil in three of the largest of the Bartlesville pools (Nowata, Bird Creek, and Glenn). The thinning toward this no-sand area and the resulting trapping of the oil in the eastward extending lobes of the main sand body give rise to a reservoir condition very similar to that of the truncated Woodbine sand of the East Texas field. A similar condition in relation to the sand body shown at the extreme left of the map accounts for the accumulation of oil at Burbank, also the Yale-Maramec field. The accumulation of oil at Cushing[1] is due to both structure and thinning of the sand.

[1]T. E. Weirich, "Cushing Oil and Gas Field, Creek County, Oklahoma," *Structure of Typical American Oil Fields*, Vol. II (Amer. Assoc. Petrol. Geol., 1929), pp. 396-406.

The profile (Fig. 2) shows that this sand at the west really occurs at a slightly different horizon in the Cherokee shale from the main body of sand. This fact has given rise to a difference of opinion as to whether it should be called Bartlesville, some preferring to use the name Burbank or Red Fork. The profile also shows the general structural condition of the sand to be that of a monocline dipping westward at the rate of about 30 feet per mile. There are many small "structures" in the Bartlesville that have caused small producing fields, but such production is much less important than that caused by changing porosity and the eastward thinning of the sand body.

WATER IN BARTLESVILLE SAND

Analyses of water from the Bartlesville sand show it to be connate, the total concentration of solids being several times that of sea water. It is probable that water from the sand near the outcrop would show some penetration of meteoric water, but as there is no outlet for it after entering the sand, excepting the relatively small amount which is withdrawn through the wells drilled into it, there is little chance for meteoric water to penetrate far into the sand. Nearly everywhere, the sand is saturated with water wherever the pore spaces are not filled with either gas or oil. In most places, where wells penetrate the sand without finding either gas or oil, water rises in the hole very quickly; if it does not, the reason is either a lack of porosity or a lack of hydrostatic pressure because of being in an isolated sand body or on the up-dip thinned-out edge of the sand.

CONDITIONS OF WATER AND OIL PRODUCTION

Nowata area.—A detailed description of the Nowata area was written by Edward Bloesch.[1] The Nowata field comprises one of the oldest producing areas of the state. Development was active during the years 1904 to 1911. Production extended almost continuously a distance of 14 miles. The Bartlesville sand is variable in thickness and, in some places, is separated by shale partings into members, one or more of which may prove productive in any well. There is almost a complete lack of water in the area, although some water does occur at the extreme northwestern edge of the Delaware Extension field and at an isolated spot or two on the west side of the main field. This absence of water is readily explained by the relation of the field to the main sand body as shown

[1]Edward Bloesch, "Nowata and Craig Counties," *Oklahoma Geol. Survey Bull. 40-EE* (June, 1928).

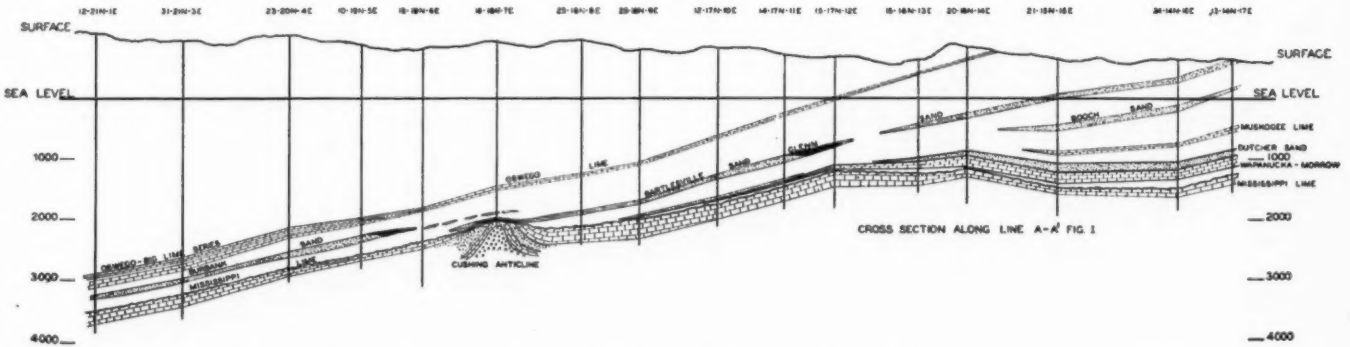

FIG. 2.—West-east cross section, showing stratigraphic position and correlation of Bartlesville sand in northeastern Oklahoma. Location, *AA'* in Figure 1. Length, approximately 110 miles. Section, township, and range shown at top of section. Depths in feet.

on the map (Fig. 1). It may be said that water has been neither a menace nor a help to the production in this area.

Bird Creek pools.—This area is really a group of fields, much more discontinuous than the other producing fields shown on the map. It is interesting because it is caused by the eastward thinning of the sand. It is one of the large producing areas of the Bartlesville sand, though it is seldom thought of as such and has not been described in detail. Water production per well in this area is greater than in any of the other fields shown, being approximately 6½ barrels per well per day, and oil production is about one-third of that amount per well per day. Depth to the sand is about three times as great as in the Nowata area and the hydrostatic pressure of the water should be greater because of this fact and also because it is much closer to that part of the sand which is connected continuously with the outcrop as shown on the map (Fig. 1).

Burbank field.—The Burbank field is described in a paper written by J. M. Sands.[1] This field lies along the eastern extremity of an isolated sand body and the water conditions are entirely in harmony with its position. The producing area is connected with the rest of the sand body for only a short distance along the west side of the field. In the early stages of development, a strong hydrostatic head existed west of the field, where the sand was present. It is thought that this was due to the back pressure of the oil and gas on the oil-water level, for, after the field was developed and the reservoir pressure was low, this hydrostatic head disappeared. Some bottom water occurs in nearly all parts of the field, but it is thought that this water was always present, as it does not increase in volume, and as the water in any particular well decreases, the oil production decreases also. It is an interesting fact that the average water production is about twice as great in the western half of the field as in the eastern part and the oil production is also in the same ratio. This is a strong indication that the presence of water, even though it is not under great pressure, is beneficial to both the rate of production and the ultimate recovery of oil.

The Burbank field was developed during the years 1921-1924, so that much better records are available than the records of fields drilled early in the history of Oklahoma production. A few more than 2,000 wells were drilled, draining an area of approximately 21,000 acres. A total of 174,029,351 barrels of oil were produced up to January 1, 1932, giving a per-acre yield of 8,268 barrels. With a daily production of

[1] J. Melville Sands, "Burbank Field, Osage County, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. II, No. 10 (October, 1927), pp. 1045-54.

about 12,000 barrels at the present time, the average daily production of oil is 6 barrels per well, with a water production of half that amount, or 3 barrels per well per day. It is evident that the total ultimate recovery per acre will not exceed 9,000 barrels from the ordinary flowing and pumping methods. This is not more than half the ultimate recovery that was anticipated for the field during the early stages of its development based on the average thickness of the pay horizon and its porosity. It is no secret that the recovery of the field as a whole has been very disappointing. The Rainbow Bend field of southeastern Kansas produces from the same horizon as Burbank; the general conditions surrounding the field are very similar to those at Burbank, gas being the only expulsive force in the sand. Here again, the average recovery per acre has been little more than half of that which was expected (approximately 7,500 barrels, to date).

Glenn pool.—A paper describing the Glenn pool was written by W. B. Wilson.[1] From 2,580 wells, the field has produced to January 1, 1932, a total of 208,432,307 barrels of oil. The number of acres drained is about 27,000, giving a per-acre yield of 7,719 barrels. The present oil production per day is about 6,000 barrels. The amount of water produced in the field has remained practically constant for many years and at the present time is approximately 7,000 barrels per day, or an average of 2.7 barrels per well per day in comparison with an oil production of 2.3 barrels per well per day. It has been demonstrated by wells recently drilled on the southwest edge of the field that there is still a hydrostatic pressure on the sand. There have been some recent completions of wells in which water has risen to the surface, and wells drilled on the west edge of the field can easily be drowned out by bottom water if the sand is penetrated too far. It is evident from the map (Fig. 1) that there is an ample source of water to maintain the hydrostatic head as it is withdrawn with the oil production.

It seems evident from the fact that there must be a considerable pressure exerted against the portions of the sand which are saturated with oil, that these oil-saturated sand bodies offer a tremendous resistance to the encroachment of water and that such resistance has effectively acted to prevent the migration of water into the sand. Those most familiar with conditions in Glenn pool and in the other fields previously discussed, are of the opinion that a very small percentage of the oil has been extracted from the sand. If the hydrostatic pressure known to be

[1]W. B. Wilson, "Geology of Glenn Pool of Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 10 (October, 1927), pp. 1055-65.

present were an effective repressuring or expulsive force, the amount of oil recovered would have been much greater than that which has been taken out and mechanical means of repressuring, which are being used effectively, would be unnecessary.

CONCLUSION

It is an interesting fact that the total area of the large fields producing from the Bartlesville sand of northeastern Oklahoma is about the same as the total area of the East Texas field; the average thickness of saturated sand is fully as great as in East Texas; and yet these fields have produced an average recovery of only 8,000 barrels per acre, or a total of about 800,000 barrels. It is interesting, too, that the per-acre recovery of each of the large Bartlesville fields varies but little from the 8,000-barrel average. This low recovery per acre is a very small percentage, probably not more than 15 per cent of the total oil content of the saturated portions of the sand, and is evidently due to the fact that there has been no effective water drive in any of these fields and that gas has been the only expulsive force. It is regrettable that we do not have more exact figures for the thickness, porosity, and permeability of the oil-saturated portion of the Bartlesville sand and it is probable that at some time in the future such information will be obtained by drilling additional wells.

From a study of the map and Figures 2 and 3, representing the relation of the oil-sand reservoir to the water-saturated portion of the sand

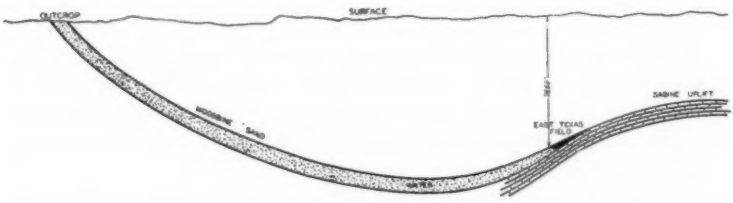

FIG. 3.—Diagrammatic west-east cross section of Woodbine sand basin, showing location of outcrop in East Texas field, and Sabine uplift. Depth to water-saturated part of oil-sand reservoir, 3,650 feet.

body in the Glenn pool and East Texas, respectively, it is seen that the conditions affecting the hydrostatic pressure in the two fields are very similar. From this, one would be led to think that water encroachment would probably not be more rapid or more effective in East Texas than it has been in the Glenn pool. However, there are two very important points of difference.

1. The hydrostatic pressure on the western edge of the East Texas field is more than twice as great as that along the western edge of the Glenn pool, being represented by a column of water approximately 3,650 feet high in East Texas as compared with a hydrostatic pressure represented by a column of water 1,650 feet high at the Glenn pool. This is a very important difference and it can easily represent the difference between an effective and an ineffective pressure.

2. Another important difference arises from the fact that the average porosity of the Woodbine sand (and of still greater importance, its permeability) is considerably greater than that of the Bartlesville sand. This condition of greater porosity and permeability would decrease greatly the resistance offered by capillary interstices between sand grains to the encroachment of water and increase greatly the effectiveness of water flushing in the East Texas field, provided the production from the field is controlled so that the water may have an opportunity to advance evenly along the water-oil contact without by-passing the oil and shutting it off from future recovery.[1]

Late information from bottom-hole pressure readings points strongly to the conclusion that there is going to be an effective water drive in the East Texas field. If this water encroachment is properly controlled by keeping the allowable output of the field at a low figure, it should at least double the recovery over that which could be expected if such a water drive does not take place. This conclusion is based on the fact that in those fields where there has been no effective water drive (for example, the Bartlesville sand fields previously described), although other conditions were very similar, the ultimate recovery of oil by natural flow and by pumping has been very disappointing and is much less than would have been calculated on a theoretical basis from the known thickness, porosity, and saturation of the sand. Another situation pointing to the same conclusion is the fact that the decline in bottom-hole pressures in the East Texas field during the period of heavy withdrawals was at such a rate as to indicate an ultimate recovery per acre of much less than that which it was calculated should be recovered, based on sand thickness, porosity, and saturation. Actual per-acre recoveries ranging from 35,000 to 40,000 barrels from other Woodbine-sand fields where there has been an effective water drive point to the same conclusion.

[1] For classifications of types of oil reservoirs and principles of production from them, see Stanley C. Herold, *Analytical Principles of Production of Oil, Gas, and Water from Wells* (Stanford Press, Stanford University, California, 1928).

The bottom-hole pressure readings already referred to indicate that the slow rate of withdrawal, which has been permitted during the last two or three months in East Texas, is allowing sufficient time for water to advance along a uniform front and to maintain the reservoir pressure at very nearly a constant figure. Time is an important element in an effective water drive. Therefore, if the greatest benefit is to be derived from this repressuring force of the advancing water, the oil should not be withdrawn from the reservoir at a greater rate than the water can enter the sand along a uniform front. It should be possible to determine this rate of advance by determining the rate of flow at which bottom-hole pressures decline most slowly.

As oil fields become increasingly difficult to locate, this problem of securing a much greater recovery of the oil known to be in the sand is going to be one of the greatest problems confronting the oil industry, and it seems likely that proration, although forced upon us against our will, may contribute much information toward its solution which would otherwise never have been obtained.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 9 (SEPTEMBER, 1932), PP. 891-906, 4 FIGS.

GEOLOGICAL APPLICATION OF BOTTOM-HOLE PRESSURES[1]

C. V. MILLIKAN[2]
Tulsa, Oklahoma

ABSTRACT

Bottom-hole pressure is the pressure measured at the face of a porous reservoir penetrated by a well. There is not as yet sufficient history of bottom-hole pressures in different fields during development and depletion to make possible a full interpretation of pressures which may be taken. Experience thus far shows that they may be a valuable aid in correlating porous formations, determining reservoir conditions, rate of development and proper well spacing, and estimating reserves and the most economic rate at which the oil may be recovered. With more experience in the interpretation and correlation of bottom-hole pressures, their value will increase greatly.

DEFINITION

Bottom-hole pressure, or depth pressure, is the pressure at or near the bottom of a well. It is usually determined at the face of a porous reservoir of sandstone or limestone, penetrated by the well. If the well has been shut in or shut down long enough for the pressure at the face of the sand to equalize with the pressure in the reservoir within the drainage area of the well, it may be called the reservoir pressure. If the bottom-hole pressure is determined while the well is producing, it may be called the bottom-hole flowing pressure or bottom-hole producing pressure.

VALUE OF BOTTOM-HOLE PRESSURES

The possible value of bottom-hole pressures in the development and operation of oil fields has long been recognized, but only during the past two years have instruments been available that could be used to determine them consistently, accurately, and economically, and it is only during the past year that their use has become sufficiently general so that their value has been proved. Though the time that bottom-hole pressures have been used is short and in spite of the fact that the history of changes of bottom-hole pressures with the development and depletion

[1]Read before the Association at the Oklahoma City meeting, March 25, 1932. Manuscript received, April, 1932. Published by permission of the Amerada Petroleum Corporation.

[2]Production engineer, Amerada Petroleum Corporation.

of oil fields is limited, the pressure data are already valuable information for the geologist, the engineer, and the operator.

Bottom-hole, or depth pressures, give many data on reservoirs and reservoir conditions, and on movement of oil, gas, and water through the reservoir. Determinations of reservoir pressures in a field through a considerable period of time indicate the size of the reservoir and the rate of water encroachment. The relative permeability and porosity of the sand may be determined from bottom-hole producing or flowing pressures. The time required for pressure changes in one well to be reflected in an adjacent well is important when considering the most advantageous rate of development and spacing of wells. The knowledge of the pressure in the reservoir is necessary to determine the energy available to move the oil through the sand to the well. In addition to these problems in which the geologist is primarily interested, bottom-hole pressure data aid in solving many problems in development and operation of fields and of individual wells.

ORIGIN OF RESERVOIR PRESSURE

The pressure in a porous reservoir may be a result of genesis of the oil and gas, compaction of beds, overburden, reduced porosity by deposition from solution, or hydraulic head maintained by water in a reservoir extending continuously to a higher elevation.

Genesis of oil and gas and compaction of beds are probably the most important. If the theory be correct that oil originates from destructive distillation of organic matter under high pressure and high temperature, there must be pressure before the oil is formed. The pressure would result from compaction from overburden. If, in this process of oil forming, conditions are such that the amount of gas formed is greater than that which will dissolve in the oil at the existing pressure and temperature, the free gas may tend to occupy more space than its source material and the pressure will be increased. Overburden as it exists now is probably of little effect on reservoir pressure, but the subsidence which has occurred at Goose Creek and Sour Lake, Texas, and Lagunillas, Venezuela, shows that in some cases it may be important. Reduction of pore space by deposition of salts from solution has not been an important direct cause of reservoir pressures, but by sealing reservoirs and preventing free migration of oil, water, or gas, it no doubt has had an important effect on the pressures in many reservoirs. Hydraulic head is often assigned as a cause of reservoir pressure when it is of little effect. The pressure due to hydraulic head can be no more than the hydrostatic head

of water to the lowest point of outcrop, or if no part of the reservoir reaches an outcrop, to the highest point in that same reservoir. A formation may be present continuously throughout a large area, yet contain many separate and distinct reservoirs, and each of these reservoirs has pressure conditions peculiar to itself. More geological attention to the causes of reservoir pressure will be very helpful in the future.

PRESSURES IN DIFFERENT RESERVOIRS

The pressure that may exist in reservoirs that are encountered in drilling wells is especially important. Tests have shown that there is seldom any relation between depth and pressure. In one lease in the Seminole field, the following pressures were found.[1]

Formation	*Depth (Feet)*	*Pressure (Pounds)*	*Equivalent Head of Fresh Water (Feet)*
Misener sand	3,967	988	2,276
Hunton limestone	3,980	1,520	3,502
Simpson dolomite	4,068	1,152	2,654
First "Wilcox" sand	4,124	637	1,467
Second "Wilcox" sand	4,217	800	1,843

During the early development of the Seminole field, a large number of costly fishing jobs were caused by the drilling bit becoming frozen or stuck, evidently from sand packing tightly around it. At that time means were not available for determining the pressure conditions in the hole. Subsequently reservoir pressure data have been taken which prove the large difference in pressure which may exist in reservoirs which are separated by only a few feet of strata. It seems probable that most of those fishing jobs were caused by drilling through one reservoir into another of lesser pressure. While being drilled through the first reservoir, the hole would fill with oil until the head of oil was equal to the reservoir pressure. When the lower reservoir was penetrated, the oil flowed from the upper into the lower reservoir, causing the sand cuttings in the hole to pack around the bit.

Similar conditions were found in the Hobbs field, New Mexico.[2]

Formation	*Depth (Feet)*	*Pressure (Pounds)*	*Equivalent Head of Fresh Water (Feet)*
Sand	3,200	1,850	4,263
Sand	3,600	1,665	3,836
Limestone	4,100	1,523	3,509

[1]C. V. Millikan and C. V. Sidwell, "Bottom-Hole Pressures in Oil Wells," *Trans. Amer. Inst. Min. Met. Eng., Petrol. Div.* (1931), p. 199.

[2]R. S. Christie, "Reservoir Pressures in the Hobbs Field, New Mexico," *Trans. Amer. Inst. Min. Met. Eng., Petrol. and Tech. Div.* (1932), p. 342.

It will be noted that the gas sands at 3,200 and 3,600 feet both have pressures higher than the pressure of a column of water at the same depth. It was the high pressures in these two formations, particularly the former, that caused the greatest trouble and extra expense of drilling wells in the Hobbs field.

In drilling wells, especially wildcats, it is important to consider the reservoir pressure in the various porous formations which may be penetrated. If an oil and gas sand were penetrated in which the pressure is as high as the head of the drilling fluid, oil and gas would appear in the circulating mud; if higher than the head of drilling fluid, a "blow-out" might occur; if lower, it might be possible to drill through the sand with no indication of oil and gas unless the cuttings were carefully examined. For example, the original pressure in the "Wilcox" sand in the Seminole area was probably less than 800 pounds. If such a reservoir were drilled into with a rotary drill, mud being used weighing 9½ pounds per gallon (specific gravity, 1.14), the pressure at 4,100 feet would be 2,030 pounds, which is 1,230 pounds higher than the pressure in the reservoir. With so much effective pressure against the sand, some fluid would pass from the hole into the sand, and if the size of pores were large enough for the mud to penetrate, circulation would be lost, and the drilling fluid would drop to a level of 2,483 feet below the top of the hole. It is a common occurrence to lose some of the circulating mud while drilling, and frequently a formation will take mud faster than the fluid is pumped into the well, in which case circulation is "lost."

The terms "cavity" and "thief sands" are frequently used, and usually convey the thought that some porous or cavernous formation has been encountered in which the voids are not filled. It is difficult to explain how a condition could have existed whereby a porous formation could have been deposited without being filled with water. The water may have been partly or entirely replaced with oil or gas at some later period. In any case, the void could hardly be expected to exist now as a vacuum. It must have contents under some pressure. When a fluid under higher pressure has access to it, it becomes a "cavity" or "thief sand." These conditions are recognized when casing off water to prevent it from flooding an oil or gas sand. This condition existed in the Smackover field when some of the upper water sands became artesian because high-pressure gas from lower formations got into the water sands.[1]

[1]H. G. Schneider, "Smackover Oil Field, Ouachita and Union Counties, Arkansas," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 70 (1924), p. 1089.

Another example is in the Lyons-Quinn pool where gas from an upper sand had access to the oil-producing sand.[1]

The continuity of a reservoir can probably be more nearly determined by comparing production and pressure decline than by lithology. Reservoir pressures show that the widespread "Wilcox" sand in Oklahoma is not one common reservoir. If it were, the pressure at any point would be equal to the head for salt water (specific gravity, 1.11) between the depth with respect to sea-level at any point and the elevation of the lowest outcrop, which is about 600 feet. At Oklahoma City, the original reservoir pressure was about 2,550 pounds at 5,200 feet below sea-level, whereas it should have been 2,800 pounds. In the Seminole area the original reservoir pressure is not known, but it probably did not exceed 800 pounds at 3,300 feet below sea-level, whereas it should have been 1,880 pounds.

Reservoir pressures give information on reservoir conditions and probable movement of oil, gas, and water in the reservoir, which are important in estimating reserves. The use of closed-in pressures of gas wells for estimating reserves is a common practice. With additional data on the changes which occur in reservoir pressures with development and depletion of oil fields, and more experience in the interpretation of pressures, it is possible that similar reasoning may be applied to oil wells. However, the interpretation and application will be much more complicated. In a reservoir which is small and contains oil and gas only, such as a sand lens, it is necessary to consider the volume of oil, the absolute volume of gas, the solubility of the gas, and the rate at which the gas comes out of solution as the pressure declines. In a reservoir in which the portion filled with oil and gas may be only a small part of a large reservoir filled with water under pressure, it is necessary to consider, in addition to the factor of gas, the amount of water encroachment which may take place as the oil and gas are withdrawn, the rate of encroachment, and its effectiveness in washing the oil from the reservoir. Even with the present limited knowledge of oil and gas reservoirs, pressures are of considerable aid in estimating reserves, and when detail study has been made of the pressure changes which take place with development and depletion of only a few oil fields, the probable error, especially in flush and semi-flush fields, may be considerably reduced.

[1]M. J. Kirwan, "Effects of Extraneous Gas on Production of Oil from Wells in Lyons-Quinn Field, Oklahoma," *U. S. Bur. Mines Reports of Investigations*, Serial 2612.

DELAYED DRILLING

The effect of delayed drilling is a problem on which there are few available data, and those available are largely relative. It has been observed frequently that wells drilled later in the life of a field have much smaller initial production than the earlier wells, due to the decrease of pressure in the field. If the time interval between completions is short, there is always a question whether the smaller well is a result of a less favorable sand condition or is due to reservoir pressure decline by dissipation through wells which were completed earlier.

Figure 1 shows the decline in reservoir pressure in the wells on a lease in the East Texas field and the effect of delayed drilling on reservoir pressure in the wells which were completed later. The dashed line is an

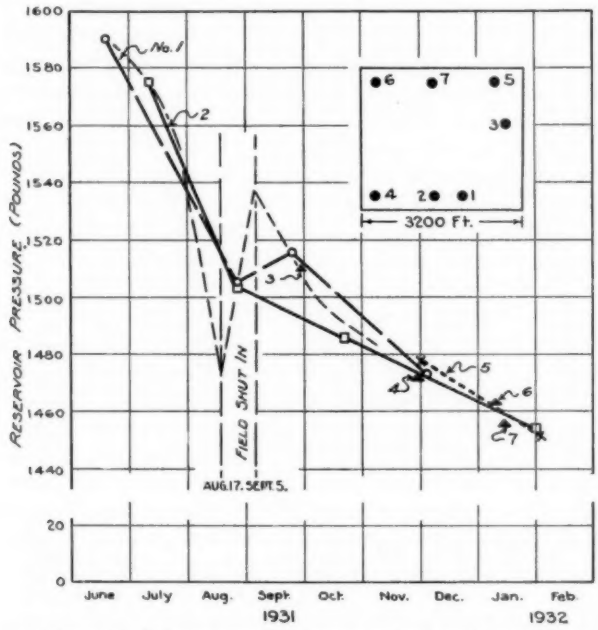

FIG. 1.—Effect of drilling on reservoir pressure under lease in East Texas field.

interpretation of the changes in the pressure which took place between the dates the pressures were actually measured. Figure 2 shows the decline of reservoir pressure in the first well and later completions in an

extension to a pool in the Seminole field which had been undergoing development for more than two years at the time the extension well was completed. Well No. 1 was the extension well. Wells No. 2 and No. 3 are located adjacent to the older development which was south and east of the lease. The plat accompanying the chart shows the relative location of the wells and the date of completion. Well No. 1 was only one location from the west edge of the pool and No. 4 made water at the time of completion.

BOTTOM-HOLE FLOWING PRESSURES

Sand conditions within the drainage area of a well are the most important factors governing the amount of oil in the reservoir, the percentage recovery, and the rate at which it may be recovered. The original reservoir content is dependent on the porosity. The amount recovered is governed by the available energy, and the rate at which it may be recovered is limited by the permeability. Porosity can be determined by analyzing of sand samples or cores. Permeability can also

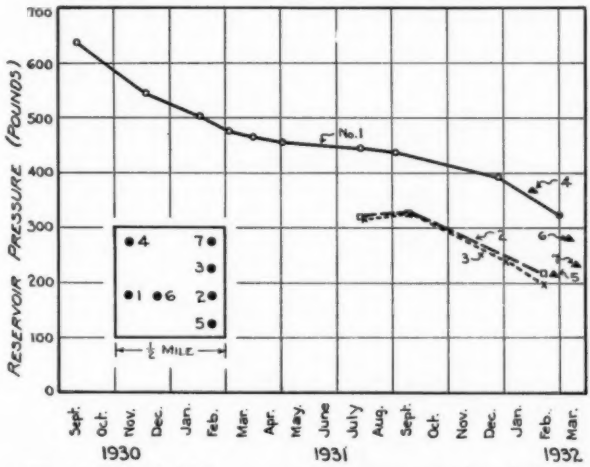

FIG. 2.—Effect of delayed drilling on reservoir pressure under lease in Seminole field.

be determined in the laboratory, but for practical purposes, the initial production is probably of greater value. The accuracy of calculations based on laboratory tests is limited to the representative character of the samples which are analyzed. In order intelligently to apply the

porosity and permeability laboratory results, other factors, such as viscosity, capillarity, surface tension, and Jamin effect, must also either be determined or be estimated. If the results are to be applied in the field by controlling production in order to obtain the recovery that the tests indicate is available, such control must be based on the differential pressure between the reservoir and the well. Such determination must be by means of bottom-hole pressures. Bottom-hole flowing or producing pressures taken in the same well permit a more practicable interpretation than laboratory determinations of porosity and permeability and perhaps eventually prove of greater value for the practical determination of these characteristics.

The flow characteristics of several wells are shown in Figure 3, in which the decline in bottom-hole pressure or the reservoir differential pressure is plotted against the rate of production. Curves *A* and *B* are of two wells in the central part of the Lathrop area of the East Texas field. The reservoir pressure was about 1,450 pounds, and the maximum rate of production shown resulted from the oil being flowed through a 1-inch choke. Curve *A* shows 16 barrels per hour less production than curve *B*, while the bottom-hole pressure declined only 24 pounds from the reservoir pressure compared with 86 pounds in curve *B*. The production through a 1-inch choke indicated that well *B* was the better well, while the bottom-hole flowing pressure tests prove that *A* is the better well. Well *C* and well *D* are also located in the Lathrop area of the East Texas field. Well *C* is close to the east edge of the field and has a very thin section of sand. Well *D* is located in the central part of the area, and penetrated 40 feet of sand, but it was recognized at the time the sand was drilled that it was not as good as most of the wells that had penetrated an equivalent amount of sand. However, there was nothing to lead to the belief that it was poorer than well *C*, as is proved by its greater decline in bottom-hole flowing pressure. The reservoir pressure in well *C* was 1,460 pounds, while the pressure in well *D* was 1,490 pounds. Well *E* is located in the Seminole, Oklahoma, field, and was producing from the "Wilcox" sand. The reservoir pressure was 412 pounds. Well *F* is also located in the Seminole field, but is producing from the Hunton limestone.

RESERVOIR ENERGY AND RECOVERY

In order to produce oil, a well must penetrate a porous reservoir filled with oil, and have associated with the oil enough energy to move the oil through the reservoir to the well. The amount of oil contained in a reservoir may be determined with reasonable accuracy from cores

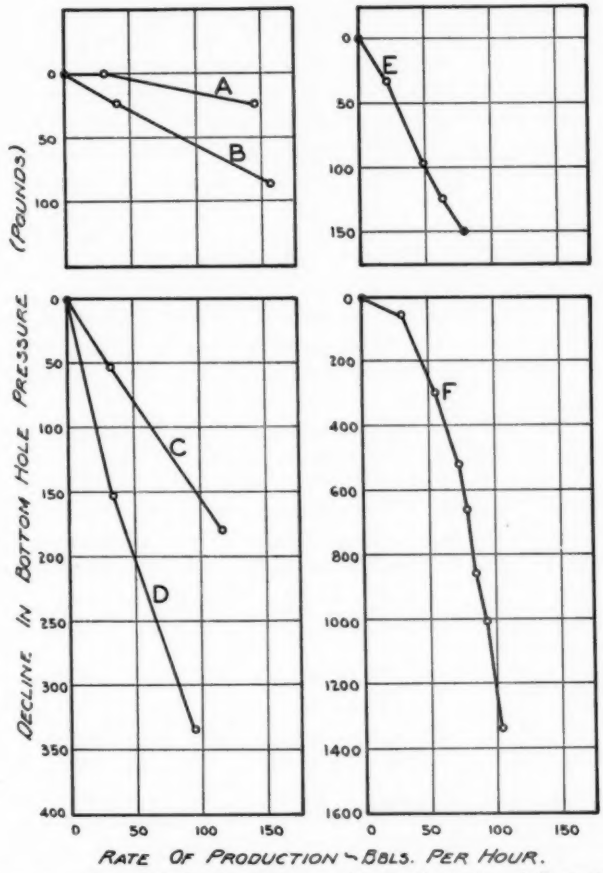

FIG. 3.—Bottom-hole flowing pressures. Curves *A*, *B*, *C*, and *D* are wells in East Texas field. Curve *E* is well producing from "Wilcox" sand and *F* from Hunton limestone, both in Seminole field.

taken of the sand, but the amount of oil that will be recovered depends upon the energy available and the efficiency with which it moves the oil through the sand to the well. The energy may be contained in the associated gas or in the water in the reservoir around the oil field.[1] The

[1]Energy from force of gravitation on the oil might also be mentioned, although the resultant recovery is very small compared with that resulting from the energy in the gas and water. Compaction from overburden, except in a few cases, is also probably of little importance.

available energy in either the gas or the water depends on the pressure and the volume. The amount of energy required depends on the amount of oil to be moved, the distance it is to be moved, the permeability of the reservoir, and the efficiency of the application of the energy. If bottom-hole pressures are taken early in the development of a field, it may be determined whether much energy may be expected from a natural water flood or whether the associated gas is the only energy available.

Reasonable initial reservoir pressures may be estimated for some of the older fields and show that the recovery obtained has been a function of the energy available at the time the field was discovered. In some fields the recovery is high because of ample energy to move the oil through the reservoir to the well, while in others with a comparable original reservoir content, the recovery has been low because of a deficiency of energy.

The ultimate oil recovery from the Burbank field, Osage County, Oklahoma, will probably be less than 15 per cent of the original content of the reservoir. The original volume of gas associated with the oil was lower than in most fields of that general area, and the energy obtained from natural water drive has been negligible. The initial reservoir pressure was about 1,200 pounds. The reservoir beyond the limits of the field is small and lower than the field so that the head of water in the reservoir adjacent to the field was low, which gave practically no natural water flood.

In contrast to Burbank, the ultimate oil recovery in the "Wilcox" sand in the Seminole area will probably exceed 50 per cent of the original content of the reservoir, because there has been ample energy to move the oil through the reservoir to the wells. The "Wilcox" sand of the Seminole area is about 1,200 feet deeper than the Burbank sand in the Burbank field. The original reservoir pressure did not exceed 800 pounds. The gas-oil ratio was probably not more than one-third that at Burbank. The average thickness of pay sand is less than in Burbank, but the average porosity may be greater. Although the volume of gas and reservoir pressure in Seminole is less than in Burbank, the part of the "Wilcox" sand reservoir which contained oil is only a very small part of the whole reservoir. The volume and head of the water were sufficient to move the oil through the sand by natural water flooding which not only flushed the oil out of the sand, but also tended to maintain the reservoir pressure as the oil and gas were withdrawn. It is the energy in the water that has given the high recovery in Seminole.

The high recovery from the "Wilcox" sand in the Tonkawa field was caused by conditions similar to those in Seminole, that is, a large general reservoir with a large volume of water available for natural flooding, but under low pressure. The initial gas-oil ratio was higher in Tonkawa than in Seminole, being about 3,000 cubic feet per barrel compared with 500 cubic feet per barrel in Seminole.

The "Wilcox" sand does not always have this volume of water available for natural water flooding. The pay sand in Stroud field, in Creek and Lincoln counties, Oklahoma, is thicker than in Seminole and as thick as or thicker than in Tonkawa, but the ultimate recovery will probably be less than 20 per cent of the original content of the reservoir. The initial reservoir pressure was at least as high, probably higher, and the gas-oil ratio was the same as in the "Wilcox" sand at Tonkawa. The Stroud field had water on all sides, but apparently the general reservoir was so small that the water advanced only a small amount until the pressure was reduced to that of the depleting field. The volume of gas energy was not sufficient to move the oil and no appreciable energy was available from the water, and the small recovery is the result.

The shallow fields in southern Shackleford and northern Callahan counties, Texas, produce from lenticular sands at about 400 feet. The average thickness is 20 feet or more, most of which is saturated with oil. Some water is ordinarily present in the lowest part of the lens, but not in sufficient quantity to cause any natural water flood. The pressure is quite low and the initial production of the better wells is 20 to 30 barrels, with 350 cubic feet or more of gas per barrel of oil. The average recovery is about 1,700 barrels per acre, which is probably less than 15 per cent of the original oil content of the sand. The low recovery is obviously due to a lack of energy, there being no water for flooding and a small volume of gas under low pressure.

If the ultimate recovery from the East Texas field depended entirely on the energy contained in the gas associated with the oil, it would probably be only a part of the most conservative estimates which are now made. The gas-oil ratio is about 350 cubic feet per barrel and all in solution at a pressure of 800 pounds or less. If there were no factor involved in the reservoir pressure other than the oil and gas content, the pressure would have declined very rapidly to the pressure at which the gas would start to come out of solution, after which the rate of decline would be slower. The recovery by natural flow would have been very small. After being put on the pump, the production would decline rapidly to a low rate which would probably be maintained for a very

long life. If only 9,000 barrels per acre can be recovered from Burbank, which is only 200 barrels per acre-foot, with an original pressure of 1,200 pounds and a gas-oil ratio of not less than 2,000 cubic feet per barrel, the expected recovery from the East Texas field with 1,620 pounds pressure and a gas-oil ratio of only 350 cubic feet per barrel would be small when compared with even the lowest estimates of recovery which are being made.

The field is in the east edge of the Woodbine formation where it is truncated against the west side of the Sabine uplift. The formation crops out on the north near the Oklahoma-Texas line, and then swings south through Cooke, Denton, Tarrant, Johnson, and Hill counties, Texas. It is exposed about half-way between Dallas and Fort Worth. It is probable that the formation is a common reservoir extending from the East Texas field to the outcrop. The original reservoir pressure of 1,620 pounds, which is very close to the calculated hydrostatic head for the field, substantiates this belief, but is not conclusive proof.

Figure 4 shows a cross section of the field, and some charts relative to the production and reservoir pressure in the field. In order to study the decline in reservoir pressure in different parts of the field in relation to the amount of oil produced, the field was divided into four sections, and the average thickness of the Woodbine sand above the water level was determined for each section. The reported recovery to March 1, 1932, for an area extending about two miles on either side of the line through which the cross section is taken was determined and reduced to recovery per acre for each section. This recovery per acre was then divided by the average thickness of the formation to give the recovery per acre-foot. The average reservoir pressure, March 1, 1932, in each section is shown in the bottom chart. All pressures have been corrected for difference in head due to difference in elevation at which each pressure was taken. It is noticeable that the recovery per acre-foot from the areas thus far is much higher for sections *A* and *D*, which have the thinnest sand, while the lowest recovery to date is from sections *B* and *C*, which have the thickest sand; also, that the average pressure in section *A* is 100 pounds higher than the pressure in section *D*, which is farthest from the water. Without correcting the pressure for difference in elevation, the pressure in section *A* would be 160 pounds higher than the pressure in section *D*.

The original reservoir pressure in the East Texas field was 1,620 pounds at 3,300 feet below sea-level. The pressure March 1, 1932, had declined only 90 pounds on the west edge of the field (section *A*) and 190

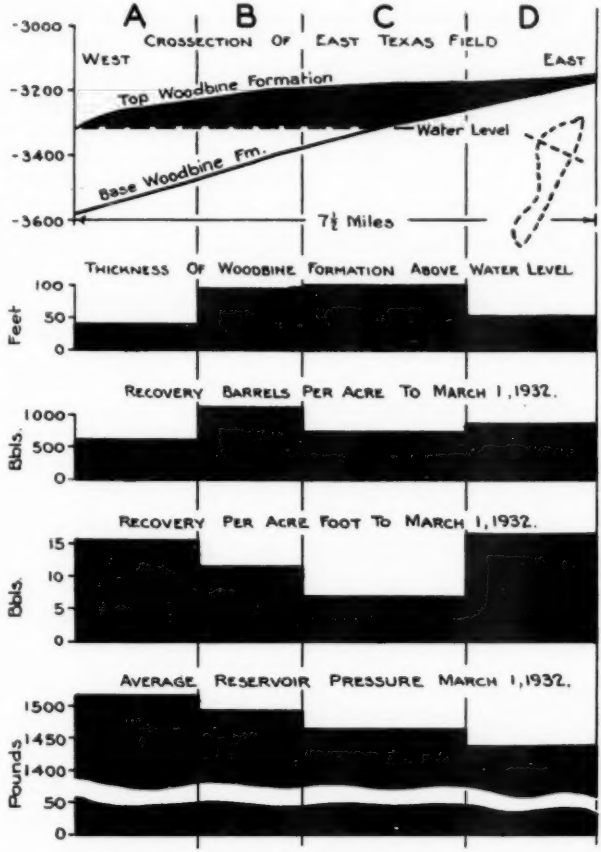

FIG. 4.—Effect of water encroachment on reservoir pressure and pressure recovery relationship in East Texas field.

pounds on the east edge of the field (section *D*). The pressure on the west side of the field adjacent to the water has been kept much higher by the water which is moving eastward replacing the oil as it is withdrawn. The effect of water advancement on the pressure is progressively less toward the east, but at present the rate of production is still having considerable effect on the pressure-production relationship on the east edge of the field.

The Woodbine formation is a sandstone with a varying amount of intercalary shale. Reservoir pressure-production relationships such as shown in Figure 4 could conceivably result from variation in sand conditions. A large area was included in each of the sections to reduce the error from this source as much as possible. Also any east-west cross section of the field would show a reservoir pressure-recovery relationship similar to that shown in Figure 4 and it would be unreasonable to expect the reservoir conditions to be uniformly good along the west edge of the field and uniformly poor along the east edge.

Bottom-hole pressures have been determined in East Texas since early in the development of the field. The more common belief that water is moving into the field from the west has been substantiated by bottom-hole pressures many months before such movement could be proved by wells on the west side actually going to water. This is important to the operators in the field, as it shows ample energy available to obtain a high percentage of recovery. However, if that high recovery is to be obtained, the rate of the water movement must be controlled by maintaining reasonably uniform reservoir pressures.

Bottom-hole pressures will permit an early determination of the source of energy upon which the recovery of the oil from a field depends. The earlier this condition is known, the more effectively may the operator plan the development program and operating procedure to obtain the greatest ultimate recovery at the least ultimate cost.

SUMMARY

There is not yet sufficient history of bottom-hole pressures in different fields during development and depletion to make it possible fully to interpret pressures which may be determined. Experience thus far shows that they may be a valuable aid in correlating porous formations, determining reservoir conditions, rate of development and proper well spacing, and estimating reserves and the most economical rate at which the oil may be recovered. With more experience in the interpretation and correlation of bottom-hole pressures, their value will increase greatly.

DISCUSSION

HARRY F. WRIGHT, Tulsa, Oklahoma (written discussion received, June 21, 1932): Mr. Millikan points out a number of facts determined by the studies of reservoir pressures, which are of outstanding importance to the geologist and which, to my mind, are worthy of careful consideration.

First, there can be no movement of fluids unless there exist differentials in pressure. This is just as true in considering the movements of fluids *into* a

reservoir as it is in moving the fluids *out* of the reservoir after it becomes a producing pool. After approximately 20 years' intensive study of oil and gas pools, and the concentration of many minds on the problem, geologists are still almost as far from agreement on the explanation for accumulation as they were at the time the anticlinal theory was proposed. The principal reason for that lack of agreement is that we have struggled along all these years without a knowledge of fundamental facts and have drawn our conclusions from results of whose causes we have been completely in ignorance.

Mr. Millikan points out at least two facts which are of prime importance in the study of accumulation of oil and gas: (1) that in a given formation there is no relation between depth and the pressure in different pools, and that while in one pool there may be present an active water drive under the influence of hydraulic pressure head, in another pool in the same formation such a condition may be entirely absent, and (2) that different formations even in the same pool and separated by only a very small vertical interval may show extreme variations in pressure.

The much-discussed, and withal widely accepted hydraulic theory postulates in principle the regional movement of connate fluids toward synclines, and the concentration of the lighter fluids into anticlinal folds by capillary and gravitational forces, either within the synclinal regions or on the way thereto. For this result to be accomplished there must be present water saturation in some degree throughout the entire extent of the formation. In short, there must be "sheet" water. A corollary effect would be uniform transmission of pressures throughout the entire extent of the formation, and the pressure at a given place would bear a definite relation to the depth of the formation below its outcrop. Discovery of the fact that there is no relation between pressure and vertical distance from outcrop, and that hydraulic head may be present at one point within a given formation and absent at another, robs the theory of regional accumulation by hydraulic means of most of its force.

Again, the proponents of vertical accumulation across the bedding planes from one formation to another stratigraphically different, except where the two are placed in juxtaposition by faulting, overlap, or other abnormal condition, leave much to ponder in the wide variation in formation pressure between horizons separated by only thin intervals. Surely migration should be possible from Misener sand to Hunton limestone through an interval of only 13 feet and with an effective pressure differential of 532 pounds, as shown in the table of formation pressures in the Seminole field of Oklahoma.

The use of closed-in pressures in estimating reserves doubtless will be of vastly increasing importance as data are accumulated. Gas reserves have been estimated for years by this method and with entire success. Application of the principle to oil reserves will not be so simple as its application to gas, but I can not agree with Millikan that it will be especially complicated. Many of the factors named by him, such as solubility of gas and rate at which it comes out of solution, viscosity, porosity, and permeability, and perhaps other factors, will be automatically reflected in the slope of a production-against-pressure decline curve. Certain of these factors are just as important in gas as in oil fields, yet failure to consider them individually has not appreciably detracted

from the accuracy of estimating quantities and the rate of decline in production from gas wells.

Some very interesting and instructive facts are set forth in Figure 4, showing various relations between four arbitrary zones in the East Texas field. It seems to me that the figures on recovery per acre, and per acre-foot, as calculated to a specific date, are misleading unless consideration is given to the number of wells, their average age, and/or the total number of feet of sand penetration. It is quite possible, and indeed even probable, that recoveries in Zone *C*, which has the thickest sand, would be higher than thinner sand zones if compared on total sand-feet drilled or on a well-acre or a well-day basis.

The measurement of reservoir pressures is bringing to us a knowledge of fundamental facts which to my mind is second to no other method of approach to the solution of geologic problems. The store of facts so far accumulated is pitifully small, yet some of our ideas already must be radically revised.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 9 (SEPTEMBER, 1932), PP. 907-914, 2 FIGS.

INTERPRETATION OF BOTTOM-HOLE PRESSURES IN EAST TEXAS OIL FIELD[1]

E. V. FORAN[2]
Fort Worth, Texas

ABSTRACT

Study of bottom-hole pressure in the East Texas oil pool has continued with the development of the field, resulting in the following information about reservoir conditions. The producing horizon is very sensitive to high differentials in reservoir pressure resulting from disproportionate drainage. The water head on the west side of the field can not maintain reservoir pressure properly except under conditions of proportionate and restricted withdrawal. The average well stops flowing when reservoir pressure is less than 800 pounds per square inch. The oil is unsaturated.

Among the more important aspects of the development of the East Texas oil field (Fig. 1) to date are the observation and determination of the bottom-hole pressures. Though the study of subsurface or bottom-hole pressures is now somewhat common in many pools, the East Texas pool is the first case in which work of this type has been carried on simultaneously with development from the early stages of the field.

The first work in subsurface pressure determinations was made during May and June, 1931, and was confined to a somewhat restricted area; but by August 15 of that year sufficient data had been obtained in the different parts of the pool to establish a definite trend of the physical changes to which the producing reservoir was being subjected. The instruments used in this early type of work were of two types, one of which recorded pressures continuously and the other intermittently. The data obtained from such instruments would of course show both the relative and quantitative changes in pressures whenever periodic observations were made on the same well or in the same area. The bottom-hole pressure, when determined under conditions of shut-in equilibrium, may be considered as equal to the maximum reservoir pressure existing within the normal drainage area of the well and is generally termed the reservoir pressure. Bottom-hole pressures may also be determined

[1]This paper has been modified and enlarged from a paper presented on April 14, 1932, at Tyler, Texas, at the spring meeting of the Division of Production of the American Petroleum Institute. It was revised, June 3, 1932.

[2]Consulting petroleum engineer, 632 Fort Worth Club Building. Introduced by F. H. Lahee.

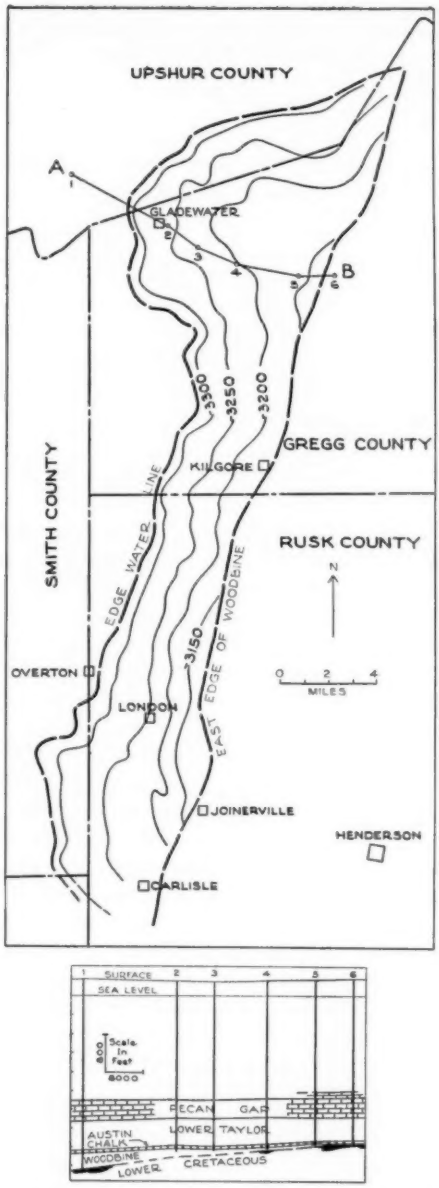

FIG. 1.—Map and section showing subsurface structure of East Texas oil field. Compare with pressure data in Figure 2. Contours are subsea, on top of Woodbine pay formation. *AB*, line of section. Solid black in section represents Lower Cretaceous where penetrated in drilling. Note that Woodbine formation wedges out eastward. After F. H. Lahee, "Contributions of Petroleum Geology to Pure Geology in the Southern Mid-Continent Area," *Bull. Geol. Soc. Amer.*, Vol. 43, No. 4 (December, 1932), Fig. 8.

while the wells are producing, in which case they may serve to indicate the productive ability of the wells under different known bottom-hole conditions such as thin and thick pay sections and sands of high and low permeability. In this case the difference between the shut-in equilibrium pressure and the bottom-hole flowing pressure, for any observed rate of flow, serves as an index of the nature of one or more of the known bottom-hole conditions previously mentioned.

For general comparative purposes in discussing the subject of bottom-hole pressures with respect to the pool as a whole, the time interval from June 1, 1931, to March 1, 1932, may be subdivided into three stages: (1) the period of unrestricted production prior to August 17, 1931; (2) the readjustment period of restricted flow from September 5, to December 1, 1931; (3) the period of restricted production from December 1, 1931, to March 1, 1932.

PERIOD OF UNRESTRICTED PRODUCTION

Bottom-hole pressure determinations were not made in the field until after 250 or 300 wells were completed; nevertheless, the observations during the months of May and June in the outlying portions of the field indicated clearly that the initial reservoir pressure must have been not less than 1,650 pounds per square inch, corrected to a level of 3,300 feet sub-sea. All pressure data throughout the field have been corrected to this level in order to eliminate any differences in pressure which might be due to differences of elevation on the structure. In other words, the depth to which the pressure-recording instruments are lowered into the well is a factor of the pressure existing at these depths. A condition of true pressure equilibrium in the reservoir therefore permits higher pressures in the lower portions of the structure than exists at the same time in the higher portions of the structure.

Many of the pressure determinations made during the months of June, July, and August indicated unmistakably that areas of abnormally lower pressure were developing in those portions of the field from which heavy withdrawals of oil prevailed (Fig. 2A). As a result of unrestricted withdrawals in the Kilgore area during the month of May and early in June, water appeared in a few of the wells which had penetrated deep into the "pay." On pinching in these wells, after the appearance of water was observed, an abrupt rise in the bottom-hole shut-in pressure was noted. This reaction not only indicated that continual abnormal withdrawals resulted in instituting a local water hazard, but also indicated the inability of the reservoir to maintain subsurface pressures of the

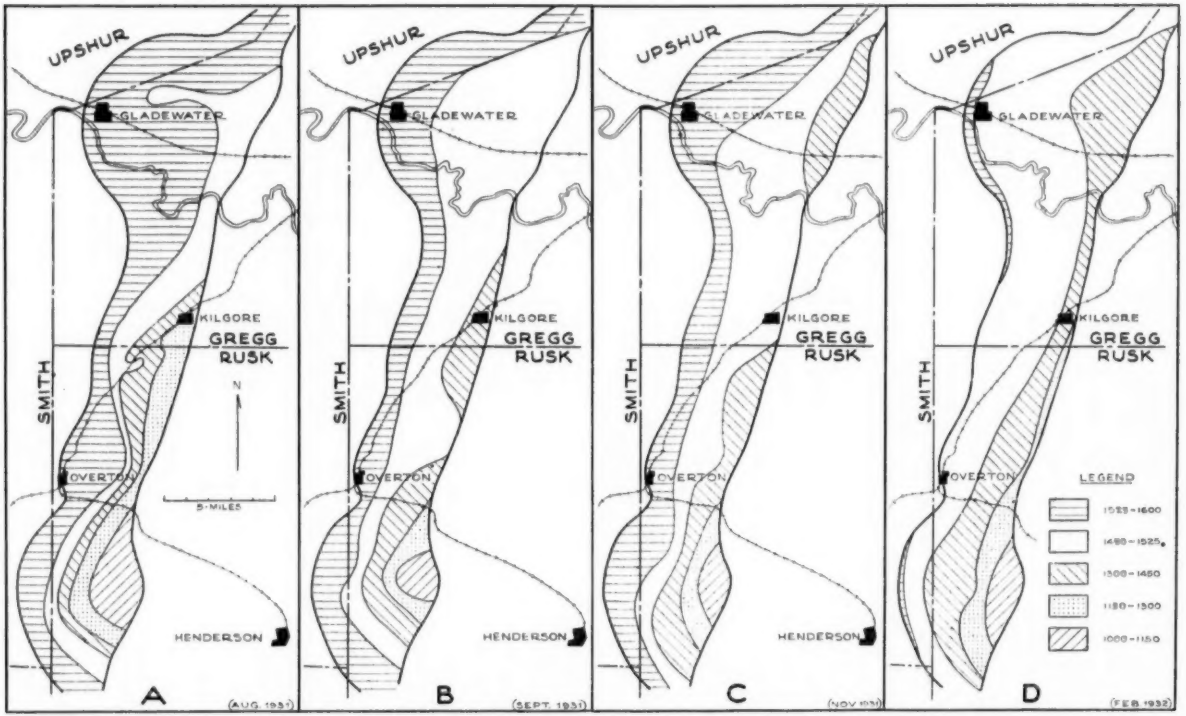

FIG. 2.—Four charts showing progressive changes in bottom-hole pressure data from August, 1931, until February, 1932. Boundary lines of pressure areas are generalized. All pressure values corrected to subsea base of −3,300 feet. Scale in *A* and legend in *D* apply to all four maps.

necessary order for the best interests of the pool. However, there prevailed prior to August 17 a great many other abnormal withdrawals in concentrated areas which were adjacent to shut-in and partly shut-in wells as well as in wholly undeveloped areas. As a result of this condition many subsurface physical changes were taking place which could only be determined through the observation of bottom-hole pressures.

The period prior to August 17 would be considered very early in the life of the field; nevertheless, the range of subsurface pressures at this time varied from a maximum of more than 1,600 pounds per square inch in the West Joiner area to pressures of less than 800 pounds in the East Joiner area. A somewhat similar condition prevailed in other areas, although not nearly to such extremes. As a result of the practices of the period of unrestricted production, there were therefore set up many local areas having relatively higher and lower reservoir pressures adjacent to each other. Under such conditions it is obvious that the prevailing direction of drainage would be from the areas of higher pressure to those of lower pressure, the magnitude of the drainage depending on the differences in pressure existing between the areas and the distances between the areas themselves. Since these conditions existed in the early development of the pool, it indicated that some immediate regulation was necessary for the protection of the undeveloped reserve against the premature depletion of the reservoir energy. Pending the necessary procedure to bring about a state of orderly development and production, the entire pool was shut in on August 17, 1931, and reopened on September 5, 1931.

READJUSTMENT PERIOD OF RESTRICTED PRODUCTION SEPTEMBER 5 TO DECEMBER 1, 1931

On September 5, 1931, the pool was reopened and production was allotted on a basis of 225 barrels to each well in the field regardless of its acreage or position with respect to other wells. This new situation being in such sharp contrast to that of the preceding period, it would be natural to expect subsurface pressure readjustments and changes commensurate with the changes taking place with respect to the new order of drainage. Also it might be expected that during the period of complete shut-down the tendency of the subsurface pressures would be toward a new equilibrium. Actual observations and examinations by means of bottom-hole pressure instruments showed a marked rise in reservoir pressure in the areas which had shown low or subnormal pressures just prior to the shut-down (Fig. 2B). The East Kilgore area, the East

Joiner area, the Lathrop area, and the Gladewater area all showed considerable recovery of pressure above that which existed prior to the shut-down. Any rise in the pressure in these areas during the shut-down period must have been accomplished by a transfer of oil and gas from the adjacent areas of higher pressure.

The process by which the subsurface pressures were seeking a new equilibrium, following the shut-down, continued until as late as the middle of October. These major underground changes indicated that a condition of primary and secondary drainage prevailed. The primary drainage may be considered as the drainage of the oil through its normal path of least resistance at the nearest well. While this process was going on with respect to all of the individual wells, there was also the slow but certain transfer of oil and gas reserves from the sparsely drilled areas to the more densely drilled areas (Fig. 2C).

Although this condition represented a marked improvement over the period of unrestricted production, it still permitted rather high inequalities of reservoir pressure to exist in various parts of the pool. As a whole, the pressure conditions in the pool during the month of November were far more nearly uniform than those of the unrestricted period; nevertheless there were many cases of local disturbance which could not be absorbed during the readjustment period, since the drainage during this period was directly proportional to the drilling density in the different portions of the field. Thus any densely drilled local area of the field might drain at several times the rate of an equal adjacent area which might have only a few producing wells.

PERIOD OF RESTRICTED PRODUCTION DECEMBER 1, 1931, TO MARCH 1, 1932

During the period from December 1, 1931 to March 1, 1932, the allowable production per well varied from 125 barrels to 75 barrels daily. This resulted in a more proportionate drainage throughout the field as a whole than existed during the previous three months and was reflected as such in the observed bottom-hole pressures (Fig. 2D). Though it is true that there was a drop in pressure throughout the field during this period, this decline was of a much lower magnitude than that of the previous period. At the same time the drainage became effective in the newly drilled areas which, during the former period, were undeveloped reserves. By February 1, 1932, the only areas of the field having pressures of more than 1,525 pounds per square inch were limited to the West Gladewater area and the Smith County area. Under the present restricted production the pool has shown a higher ability to maintain the

subsurface pressures than during any of the periods of the past, as a result of two factors, a fixed restricted withdrawal for the entire pool and a more evenly distributed drainage within the pool due to the progressive development of the undrilled areas. For the reason that the displacement of the reservoir contents by water can take place only from the west side of the field, it is natural to expect that the areas of higher pressure will be on the west and the areas of lower pressure will be in the extreme eastern part of the field. This is actually the case and will normally remain so throughout the life of the field.

It is of interest to note that in those areas where the reservoir pressure falls below 900 pounds per square inch, more than 90 per cent of the wells are required to pump their production. The natural deficiency of gas in this pool requires the highest possible order of pressure maintenance if long-flowing life of the wells is desired.

It is now commonly recognized that the oil in the East Texas field is undersaturated with respect to its associated gases. Therefore, the gas energy per barrel is uniformly distributed and limited throughout the field in all areas where the gas occurs wholly in solution in the oil. The energy contained in the gas in solution is in the potential form and not available as a propulsive force to perform work until the pressure is reduced to a point somewhat below 900 pounds. Since pressures of approximately 900 pounds occur in nearly all cases within the tubing, it is difficult to explain how gas in the East Texas field can be a propulsive force while still confined to the formation. Nevertheless, it is a distinct advantage at all times to keep the gas in the state of solution within the reservoir, since gas in this form serves to lower the viscosity of the oil and facilitates the flow of the oil toward the well. Under this interpretation, the prevailing pressure gradient between the edge water on the west (Fig. 1) and any producing well within the area in which the gas still remains wholly in solution, is due entirely to the resistance of the formation to the flow of liquids and is in no sense related to the energy of gas expansion. Accordingly, the observed low-pressure areas confined within the limits just described do not indicate depletion, but are undesirable from the standpoint of the expected flowing life of the well, since too rapid a drop in pressure will lead to premature pumping. It is obvious also that the wells confined to the sparsely drilled areas are capable of draining efficiently at higher daily rates with lower pressure gradients than wells in any of the more densely drilled areas.

If the formation of free gas within the drainage area of the well does not result in an increase in the gas-oil ratio, no waste will occur. But if

free gas, developed in the drainage area of the well, results in abnormally high gas-oil ratios, it will bring about increased water displacement per barrel of oil produced, because the tendency of the water will be to displace at the same rate at which the withdrawals are made.

SUMMARY

Summarized, the interpretation of the bottom-hole pressure data in the East Texas field to date indicates the following.

1. The producing horizon is very sensitive to high differentials in reservoir pressure which may develop or exist as a result of moderate disproportionate drainage of prolonged duration, between near-by wells or areas, or disproportionate drainage existing between similar areas during a short period of time.

2. The water head which is effective on the west side of the field is the principal natural agency tending to maintain reservoir pressures through displacement of the withdrawn contents.

3. The rapid decline in reservoir pressure prior to the period of restricted production is an indicator of the inability of the water properly to function as an agency of natural pressure maintenance except under conditions of proportionate and restricted withdrawals.

4. The average well is unable to continue flowing when reservoir pressures fall below 800-900 pounds per square inch.

5. Oil in the East Texas field is undersaturated with respect to its associated gases.

6. For efficient drainage and long flowing life in the pool, the highest order of pressure maintenance is desirable to keep the dissolved gases in solution in the oil.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 9 (SEPTEMBER, 1932), PP. 915-923, 2 FIGS.

IMPROVED TECHNIQUE FOR DETERMINATION OF DENSITIES AND POROSITIES[1]

H. R. BRANKSTONE,[2] W. B. GEALY,[3] and W. O. SMITH[4]
Pittsburgh, Pennsylvania

ABSTRACT

As a rapid method for routine determination of densities and porosities of rock samples, Gealy's modification of Russell's method is one of the best. An alternative procedure has been developed which eliminates various errors involved in direct, grain, and bulk volume measurements and subsequent porosity calculations. This increases considerably the accuracy of the method. It was found that mercury penetrates the pores of many samples. A protective coating of celluloid obviates this difficulty, and prevents loss of grains. The celluloid coating can be made so thin that errors due to the weight of the coating are negligible. The magnitude of errors due to this coating as well as those due to the method itself has been calculated and is given with data for typical samples.

INTRODUCTION

Several methods are available for determining densities and porosities of rock samples. These differ considerably in the rapidity as well as the accuracy with which measurements can be executed. When determinations are required on large numbers of samples, these factors are essential, and for this reason the modification of Russell's[5] method by Gealy[6] seems to be one of the best suited to routine work. In the method used by Gealy the volume of a bulk sample was measured, also the volume of the grains in this sample, and the porosity was found by difference. A source of considerable error can be eliminated by calculating porosity from bulk and grain densities, as is shown in the present article.

[1]Read by title before the Association at Oklahoma City, March 25, 1932. Manuscript received, February 11, 1932. Published by permission of the Gulf Companies.

[2]Geologist, Gulf Research Laboratory.

[3]Geologist, The Gulf Companies.

[4]Physicist, Gulf Research Laboratory (resigned Dec. 31, 1931).

[5]W. L. Russell, "A Quick Method for Determining Porosity," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10, No. 10 (October, 1926), pp. 931-39.

[6]W. B. Gealy, "Use of Mercury for Determination of Rock Specimens in Russell Porosity Apparatus," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 6 (June, 1929), pp. 677-82.

The writers wish to acknowledge the valuable suggestions and criticisms given by R. W. Clark and K. C. Heald of the Gulf Companies and by director Paul D. Foote of the Gulf Research Laboratory.

If the bulk and grain volumes of a sample are known, the porosity (P) can be calculated from its defining equation, $P = (V_b - V_g)/V_b$, where V_b and V_g are the bulk and grain volumes respectively. Russell devised a special tube for direct measurement of these quantities. Figure 1 shows the tube now used. A is a reservoir attached to two cylindrical tubes B and B' on which the displaced volume is read. A bottle (C) serves to hold the sample and is attached to the junction (D) of the tubes by a carefully ground joint. To take a measurement, a sufficient

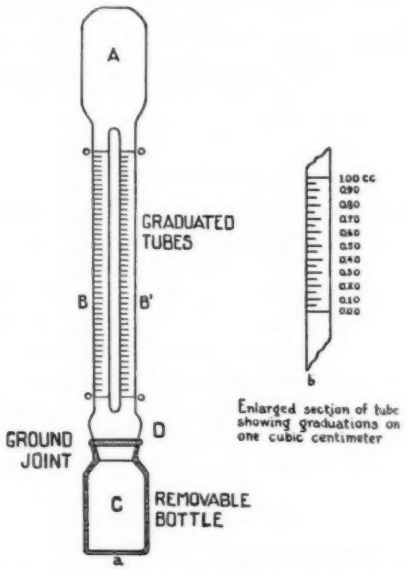

FIG. 1.—View of Russell-Gealy tube: *a*, assembled apparatus; *b*, enlarged section of tube showing graduations on 1 cubic centimeter of tube.

quantity of suitable liquid is introduced in A and a zero reading taken. The sample is placed in C and the apparatus closed. It is then inverted and the volume of displaced liquid noted. The sizes of the reservoirs A and C are adjusted to render the zero reading the same for either position.

Russell[1] used acetylene tetrachloride for measuring both grain and bulk volumes. The use of this liquid is troublesome when bulk volumes are measured, since it wets and penetrates the sample, causing errors even though the sample has been previously soaked. Gealy[2] substituted mercury to obviate these difficulties, but retained the organic liquid for grain volume determinations, where complete wetting and penetration are desirable. Considerable gain in time and accuracy was thus attained.

Gealy[3] designed a special wire basket to keep the sample submerged in the mercury. A more suitable form of cage is shown in Figure 2. It

FIG. 2.—Lower section of Russell-Gealy tube showing basket and sample in place. Points *1*, *2*, and *3* are the only points of contact between basket and tube.

is constructed of drill rod of small diameter and fits the tube rigidly. Although removable, when in the apparatus it is anchored on the graduated tubes B and B' at three points. The body of the basket is cone-shaped so that samples may be slightly wedged into position and remain immovable throughout the determination. A slight correction is required for the volume of the cage, but this volume is constant and easily determined.

Errors from any one of several sources may affect the accuracy of the determinations of porosity made by methods now in vogue. An example is the abrasion of friable samples due to handling or loss of grains in crushing. Penetration of mercury into the pores of a bulk sample causes the measured volume to be less than the actual.

[1] *Op. cit.*

[2] *Op. cit.*

[3] *Op. cit.*

PROCEDURE FOR OIL-FREE SAMPLES

A simple modification in the technique of either of the aforementioned methods will eliminate the principal sources of error, provided the samples are oil-free. The specimen is chipped to size and dried by heating for 1 hour at 100° C., cooled for 2 hours in a desiccator, and weighed. Let this weight be W_b. It is immediately placed in the cage and then inserted in the Russell tube, which was previously partly filled with mercury. The difference between the volumes of the mercury before and after inserting the specimen is that of the sample. The bulk density D_b is then

$$D_b = W_b / V_b$$

The density of the grains, commonly referred to as "grain density," is next determined. The sample, ground in an agate mortar sufficiently fine to destroy all adherence between individual grains, is transferred to the bottle of the Russell tube and then weighed. Let the weight of the grains so determined be w_g. Then the volume of the ground sample is determined as before in the Russell tube except that acetylene tetrachloride is used because of its great wetting power. Let the volume be v_g. The grain density, $D_g = w_g/v_g$, and the volume V_g of the grains in the original uncrushed sample may be obtained as $V_g = W_b/D_g$, neglecting the weight of air filling the pores. The porosity, $P = (V_b - V_g)/V_b$, expressed in terms of densities, becomes

$$P = \frac{W_b}{D_b} - \frac{W_b}{D_g} \Big/ \frac{W_b}{D_b}$$

or

$$P = \frac{D_g - D_b}{D_g}$$

$(D_g - D_b)$ is the weight of the material occupying a volume δV that would fill the pore space in a unit cube and is equal to $D_g\, \delta V$.

Obviously this procedure eliminates any possibility of error due to loss of material during the transference from mortar to tube, as would occur if one attempted to transfer the entire crushed sample, and use the volume so obtained as the true grain volume of the sample.

The natural density (D_n) can be computed from the foregoing data. This is the mass of a unit cube of the same, if it is assumed that the pore space is filled with pure water, and is given by

$$D_n = D_g (1 - P) + P$$

from which

$$D_n = D_g + P(1 - D_g)$$

PROTECTIVE COATINGS FOR SAMPLES

Loss of grains due to handling as well as immersion in mercury and subsequent shaking to dislodge air bubbles is troublesome. It is easily prevented by applying a suitable coating to each sample. Paraffine[1] is undesirable, as it can not be applied in a coat thin enough to be of negligible weight and volume.

It might appear that any lacquer would meet this requirement, but of all the materials tested only celluloid coating proved satisfactory. Even when applied in thin coats of negligible weight it was found to bind the outer grains firmly to the sample.

Celluloid lacquers are easily prepared. Filmscrap (discarded photographic film) is a suitable source. The emulsion can be removed from the film by boiling it in dilute hydrochloric acid. When thoroughly dry the clean film is dissolved in butyl acetate. This solution has the consistency of very thick lubricating oil. It is thinned somewhat with acetone, then filtered through asbestos in a suction filter. The undiluted filtrate is preferable for thick coatings, though further dilution with acetone to the consistency of light oil is necessary if thin coatings are wanted. Celluloid lacquers have a high viscosity and dry rapidly, hence penetration into the pores of the specimen coated is negligible. Even a very thin coating is sufficient to prevent loss of grains due to friability. A sample is coated by simply dipping it in the solution and drying with a lint-free towel. Removal of moisture from the specimen by oven drying should precede any coating process.

MAGNITUDE OF ERRORS DUE TO PROTECTIVE COATINGS

The effect of a thin coating may generally be neglected in density and porosity determinations. The errors in the bulk density can be easily calculated if the weight and volume of the coat on the specimen are known. From the definition, $D_b = W_b/V_b$, the error $(\delta D)_{V_b}$ in D_b due to an error δV_b in V_b is given by $(\delta D)_{V_b} = (-W_b/V_b^2)\ \delta V_b$. Similarly the error

[1] A. F. Melcher, "Determination of Pore Space of Oil and Gas Sands," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 65 (1921), pp. 469-97.

$(\delta D)_{W_b}$ in D_b due to an error δW_b in W_b is $(\delta D)_{W_b} = \delta W_b / V_b$ and the total $(\delta D)_b$ is

$$(\delta D)_b = (\delta D)_{V_b} + (\delta D)_{W_b} = \frac{\delta W_b}{V_b} - \frac{W_b}{V^2_b}\,\delta V_b \qquad (1)$$

and the percentage error

$$100\left(\frac{\delta D}{D}\right)_b = \frac{100}{V_b}\left\{\frac{\delta W_b}{D_b} - \delta V_b\right\} \qquad (2)$$

The volume of the coating on each of several samples was found from its weight and its density of 0.855 gr./cm.^{3}. This density value was determined with a specific-gravity bottle, samples of thoroughly dried lacquer being used. Weights were determined in two ways. First, non-friable samples in which the grains were not easily abraded by handling were weighed before and after coating and the weights of the coatings determined. Second, the coatings were removed with acetone in a Soxhlet extractor, and the loss of weights determined. The errors thus found are shown, together with data, in Table I.

TABLE I

MAGNITUDE OF ERRORS DUE TO THIN COATS

Sample	*Weight*	*Volume*	*Bulk Density*	*Grain Density*	*Weight of Coat*	*Volume of Coat*	*Percentage Error in Bulk Density*	*Grain Density*	*Porosity*
Shale	6.6798	2.826	2.363	2.593	.0167	.0195	.43	.51	.10
Woodbine sand	4.2172	2.160	1.9477	2.726	.0106	.0123	.32	.54	.16
Limestone	3.265	1.580	2.070	2.502	.0082	.0095	.34	.52	.13

If the coating is not extracted prior to obtaining grain densities, the error arising from neglect of this procedure can be similarly obtained and is[1]

$$\delta D_g = 1/V'_g \left\{\delta W'_g - (W'_g / V'_g)\,\delta V'_g\right\} \qquad (3)$$

Table I shows the magnitude of these errors for typical samples. The error in the porosity can be computed from the defining equation $P = (V_b - V_g)/V_b$ and is

$$\delta P = (V_g/V^2_b)\,\delta V_b - (\delta V_g)/V_b \qquad (4)$$

[1]The prime quantities refer to the weights and volumes of the crushed sample.

If the relation $P = (D_g - D_b)/D_g$ is used, we easily find

$$\delta P = \frac{D_b}{D_g^2}\,\delta D_g - \frac{\delta D_b}{D_g} \tag{5}$$

The error in the natural density D_n is

$$\delta D_n = (1 - P)\,\delta D_g + (1 - D_g)\,\delta P \tag{6}$$

The percentage error is easily calculated as in the case of bulk densities.

The errors in the porosity and natural density caused by thin coatings are shown for several samples in Table I and are seen to be negligible.

MAGNITUDE OF ERRORS DUE TO APPARATUS

The limiting accuracy of the method, controlled by the smallest volume that can be read on the Russell tube and the accuracy of the weights, can be calculated from equations 1 to 6. The smallest volume that can be read is 0.01 cubic centimeter. On the assumption that the error in weighing is not more than 0.0001 gram, percentage errors in bulk, grain, and natural densities, as well as porosity, have been calculated and are shown in Table II. The accuracy is more than sufficient for practical work.

TABLE II

MAGNITUDE OF INSTRUMENTAL ERRORS

I	*Percentage Errors in*			
	II	*III*	*IV*	*V*
Sample	*Bulk Density*	*Grain Density*	*Porosity Computed from Densities*	*Porosity Computed from Volume Determinations*
Shale	.35	.39	.10	.35
Woodbine sand	.46	.65	.13	.46
Limestone	.63	.76	.11	.63

Percentage errors in porosity as computed for the relation $P = (D_g - D_b)/D_g$ are shown in Column IV of Table II, and corresponding values are shown in column V computed from the relation $P = (V_b - V_g)/V_b$, used by Russell and Gealy.[1] They are seen to be considerably greater in the latter case.

[1] *Op. cit.*

A few simple experiments served to show the practical accuracy of the Russell-Gealy apparatus. Its reliability for bulk volumes was found by determining the volume of a spherical steel ball about the size of an average sample. The volume of the ball was found to be 3.6248 cubic centimeters when computed for a mean value of its diameter, determined by careful calibration; the volume found by the Russell tube using mercury was 3.62 cubic centimeters. The accuracy with which grain density may be determined was indicated by experiments on a 60-65 mesh Ottawa standard silica sand. Determinations made with this apparatus using acetylene tetrachloride were compared with those made with a specific gravity bottle, the same specimen being used in each case. The value 2.61 gm./cm.^{3} found with a Russell tube compares favorably with the value 2.62 gm./cm.^{3} obtained by use of the specific-gravity bottle.

PREVENTION OF MERCURY PENETRATION

Samples having exceptionally large pores are occasionally encountered and permit considerable penetration of mercury when placed in a Russell tube though coated by the procedure previously described. Microscopic examination of the fractured sample shows such penetration. With these samples, a thin coat of negligible weight is applied to prevent abrasion, after which the sample is dried and weighed. It is then coated thickly with the more viscous lacquer. When the sample has been sufficiently covered, and dried, a new weight must be taken. From these data the exact weight of the coat can be calculated. As the density of the celluloid is known, the corresponding volume may be determined. The correction is then subtracted from the total volume of the sample as measured and the true volume found. This procedure applies only to special cases.

PROCEDURE FOR OIL-BEARING SAMPLES

Many of the specimens submitted for porosity determinations contain oil. Such specimens are coated and the bulk density determined as before. They are then crushed to destroy pore space and transferred to an extraction thimble. Let W_b be the weight of the crushed sample in the thimble, and D_b the previously determined bulk density. Then the volume of the equivalent uncrushed sample V_b equals W_b/D_b and is used in all further calculations. Error due to transference of grains is thus avoided except for a preferential separation of oil and grains on the mortar and this is negligible. The oil is entirely removed by extraction with carbon tetrachloride. Carbon bisulphide is preferable with rocks

containing asphalt or asphalt-base oils. When extraction is complete the thimble with its contents is dried and weighed. Let the weight of the sample alone be W'_b. The true bulk density D'_b, which is the value for the original uncrushed sample, if it is assumed that its pores are filled with air, is then $D'_b = W'_b/V_b$. As much as possible is transferred to the bottle of the Russell apparatus and the grain density determined. The weight of grains (W_e) is taken as the actual weight in the Russell bottle. Let V_e be the corresponding volume. Then $D_g = W_e/V_e$. The grain volume (V'_g) of the equivalent sample is $V'_g = W'_b/D_g$. The porosity can then be calculated from the bulk and grain volumes of the equivalent sample, or preferably from the true grain and bulk densities from the relation

$$P = \frac{D_g - D'_b}{D_g}$$

The use of an equivalent sample eliminates tedious and uncertain corrections for loss of grains without resorting to additional weighings.

CONCLUSIONS

The procedure developed is believed to be more rapid and more precise than those described in previous papers. Moreover, it still retains the qualities which make it suitable for routine work. By substituting bulk and grain densities for bulk and grain volumes used in the original method, the error is reduced to a negligible amount.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 9 (SEPTEMBER, 1932), PP. 924-942, 5 FIGS.

FACTORS INVOLVED IN SEGREGATION OF OIL AND GAS FROM SUBTERRANEAN WATER[1]

JAN VERSLUYS[2]
The Hague, Holland

ABSTRACT

The process of oil and gas accumulation is mainly a segregation of these substances from the water circulating in the earth's crust. The segregation is caused by intermolecular forces and differences of pore size. The hypothesis that synclinal oil has accumulated in dry or unsaturated strata is rejected. Tardiness of edge-water encroachment and irregularities in the shape of oil and gas accumulations deserve attention.

The interstices of the sediments in the earth's crust form one interconnecting network of fine pores to a great depth. All these pores are filled with water except where oil or gas has replaced it. In each point of the earth's crust the water has a hydrostatic pressure approximately equal to the pressure exerted by a column of water from that point to the earth's surface above it.[3] Oil and gas must have the same pressure as water they have replaced. Consequently, they also have the pressure inherent in the depth where they occur.[4]

No other conception is possible, because most sediments have been deposited under water. The sediments which were deposited on the continents above the water must have been covered with water or have come into the water-saturated regions of the earth's crust before younger water-laid sediments had been deposited upon them. After deposition of the sediments, the volume of the pores may decrease owing to compacting pressure; therefore, the more deeply buried sediments constantly tend to discharge part of their confined water. Moreover, the expansion of the water at high temperatures exceeds the decrease of volume caused

[1]Read by title before the Association at the Oklahoma City meeting, March 25, 1932. Manuscript received, March 7, 1932.

[2]De Bataafsche Petroleum Maatschappij, Carel van Bylandtlaan 30.

[3]Jan Versluys, "The Origin of Artesian Pressure," *Proc. Royal Acad.*, Vol. 33, pp. 214-22 (Amsterdam, 1930).

[4]*Idem*, "Can Absence of Edge-Water Encroachment in Certain Oil Fields be Ascribed to Capillarity?," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 2 (February, 1931), pp. 189-90.

by compression. Temperature does not increase with depth to such a degree that the vapor pressure becomes greater than the pressure which is inherent in the depth, except in volcanic regions. Consequently, no water will evaporate at depth and no depletion of the pores can be caused by temperature. Thus, due to compaction of the strata and rise of temperature with depth, there is a constant excess of water at depth, and this water tends to rise through the overlying beds.

Regarding the occurrence of petroleum and gas, there are two main points to be borne in mind: (1) they are encountered in the coarse sediments; (2) the majority of the known oil and gas fields are restricted to the highest parts of the "structures," unless accumulation of oil and gas is caused by a fault.

The problem of how oil and gas have been concentrated, especially in the coarser strata, was not at first considered by geologists, who allowed this fact to remain unchallenged. Neither has it generally been known what filled the pores of the finer sediments. In such sediments the pores may be so narrow that the motion of liquids through them is very slow. Several hydrologists erroneously consider them to be dry and impervious. Accordingly, the coarser beds which have no exposures at the surface are often erroneously regarded as closed reservoirs.[1]

If it is taken for granted that oil and gas rise to the topmost parts of the coarser strata owing to their lower specific gravity compared with that of water, and are retained there, a certain rôle is attributed to the more finely grained strata, namely, that of barriers to the motion of the oil and gas. Often the finer strata are said to be tight. In argillaceous beds, however, there are fine pores, and these are water-filled. Great friction in such very fine pores can not be invoked to explain the reluctance of oil and gas to penetrate fine strata, because friction in liquids and gases consumes but an infinitely small amount of energy, if the motion is infinitely slow; hence, by friction oil and gas could not be retained for geological periods in coarse strata.

In a former paper[2] the writer argued that when oil or gas from a coarser porous medium penetrates a finer medium and thereby displaces water which inversely displaces the oil or the gas, the total potential molecular energy must increase; therefore, a certain amount of work must be done. This explains why oil and gas tend to remain in the coarser strata, when they have accumulated in such. In a similar way

[1] Jan Versluys, *op. cit.*, p. 192.

[2] *Idem.*

fine-grained strata act as screens, when water, charged with small globules of oil or minute bubbles of gas, is forced through them.

If the water in the pores of all the strata is supposed to be charged with small globules of oil, as previously mentioned, then in the coarser strata they are not directly in touch with the minerals and they are approximately spherical. They are separated from the grains by a film of water because the minerals are better wetted by water than by oil. Later it is explained that if there were oils in the formations for which the minerals had a greater affinity than for water, such oils would never accumulate. Therefore, consideration of the existence of such oils is unnecessary, as they would never collect in certain parts of the formation so as to be discoverable and exploitable. In coarser strata the globules can easily be entrained and follow the motion of water, as they are small compared with the dimensions of the voids of the sediments.

In very fine-grained sediments the globules are also separated from the grains by a film of water, but they may be of the same order of magnitude as the voids of the sediment, so that their form may depend on the shape of the pore in which they lie. Consequently they are, as a rule, not spherical, but many are oblong, if the voids have the form of channels. Except for the film of water which separates them from the wall, the globules cover the whole cross section of a pore and are propelled by the water.

With the spherical form the area of the surface is smallest; consequently, the potential energy of the intermolecular forces has in this form its smallest possible value. Hence a globule can pass easily from a fine layer into a coarse layer, as then the intermolecular forces come into action as they perform work. If, on the contrary, a globule has to be pushed from a coarse stratum into a fine-grained stratum, work has to be done to counterbalance the increase of potential energy of the intermolecular forces. Thus a force is needed to make the globules pass from a coarse into a fine layer, and one can say that oil and gas are averse to entering fine-grained strata.

This aversion of oil and gas, when disseminated in water, may account for their accumulation at certain points in the earth's crust. Such accumulation would occur where a current of subterranean water from a coarser layer enters a fine layer and, furthermore, where it leaves a coarser portion to enter a finer portion of the same layer.

Various reasons have been given for the aforementioned tendency of oil and gas to accumulate in the top of a fold. Most geologists ascribe it to buoyancy. That is to say, if oil and gas are supposed to be at

first dispersed in the water which fills the pores of the coarse strata, they tend to rise because of the difference in specific gravity between oil and water. Experiments, as a rule, have not given much evidence as to the opinion that small globules of oil, disseminated in the water which fills the pores of a sand, are able to rise along an overlying layer of clay which has a gentle slope. Such experiments, however, are not quite conclusive, as the time factor is too small to be comparable with the time available for accumulation in the earth's crust. On the contrary, in the earth the distances are so much greater than in the experiments that much more time is required to bring about the accumulation. The writer does not reject buoyancy as an important factor in oil accumulation at the anticline, but in his opinion other factors may also have a considerable influence.

There are different opinions as to the origin of oil. Most geologists, however, agree in assuming that oil must have migrated, as it is very improbable that so much organic matter was originally enclosed by the sediments within the limits of the present oil accumulations as to give rise to the existence of all the oil. It is more plausible that oil has been formed as small globules throughout the water in the voids of the sediments. It is a question whether oil has been formed in all the strata or only in part of them. In the opinion of several authors it is mainly formed in the finer strata. These are generally clay and are easily compressed by the weight of the overlying sediments. The water is partly squeezed out and makes its way mainly through the coarser strata.[1] The small globules of oil are carried over into the coarser strata, from which, however, they will not again penetrate easily into finer layers.

John L. Rich,[2] although adhering to the principle of an aversion of oil and gas to penetrate finer strata as stated in M. J. Munn's hydraulic theory,[3] assumed that in general the accumulation is a consequence of a change in the velocity and the direction of flow of the water which carries the globules of oil and the bubbles of gas.

An investigation into the problem of subterranean water circulation, however, leads to the conclusion that water tends to rise across the beds in the anticlinal folds, except in mountainous regions and up-

[1]Jan Versluys, "Synclinal Oil and Unsaturated Strata," *Proc. Royal Acad.*, Vol. 31 (Amsterdam, 1928), pp. 1086-90.

[2]John L. Rich, "Studies in the Application of the Anticlinal Theory," *Econ. Geol.*, Vol. 4 (1909), pp. 141-57.

[3]M. J. Munn, "Further Notes on the Hydraulic Theory of Oil Migration and Accumulation," *Econ. Geol.*, Vol. 7 (1923), pp. 213-25.

lands. Part of the meteoric water penetrates the earth's crust and percolates through the pores and drains toward the lowlands. It unites there with the percolation water of these regions and discharges into the river beds. However, a long time is necessary before this percolating water has displaced all the water which originally filled the pores of the strata underlying the lowlands; hence, the stage when the percolation water rises in many cases may not yet have been reached. The water rising in the lowlands may still, to a greater or less extent, be connate water from the deeper strata. The percolation water of the highlands penetrates not only at the outcrops of the coarse layers, but also where finer layers come to the surface. The coarse beds take care of the horizontal transportation of the percolation water — even where they have no exposures in the highlands or in the lowlands — whereas the water moves nearly perpendicularly across the finer strata.

In the highlands the motion through the finer strata generally has a downward trend, whereas under areas at lower levels it rises vertically through the finer strata. Not only does the percolation water from the highlands — or the connate water which is pushed ahead of it — in this way ascend in the lowlands, but also the excess water from compaction, as mentioned at the beginning of this paper, rises in this way. Water squeezed out by diastrophic compaction[1] contributes to the subterranean flow, but the main cause of the motion is probably the difference in altitude at the surface. On account of the pressure head of the water in the highlands and the mountains, it happens in some places that the water of each deeper coarse layer rises in a borehole to a higher level than that of the overlying beds, and this phenomenon in many low plains gives rise to the occurrence of artesian water (which has sufficient pressure head to rise above the surface of the earth). Thus one may say that the potential[2] of the subterranean water under the lowlands as a rule tends to increase with depth. The difference of potential between two adjacent coarse beds may be considerable, because of the great resistance to flow in the parting finer beds. In the same coarse bed, however, the potential, although generally decreasing from the mountains toward the middle of the plains, shows only slight variation in considerable distances. Therefore, the potential in each coarse layer is approximately the same in adjacent anticlines and synclines. This

[1] M. R. Daly, "The Diastrophic Theory," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 56 (1916), pp. 733-53.

[2] This expression has been used by the writer since 1911. In 1914 it was also used in the report of the first Interstate Conference on Artesian Water in Australia.

means that in the anticlines the subterranean water with a certain potential lies nearer the surface than in synclines, which makes the anticlines the most favorable places for the discharge of the underground water flow. Consequently most water of the subterranean flow, which follows the coarser beds longitudinally, rises vertically across both the finer beds and the coarser beds at the anticlines. (This upward motion of water at the anticlines may be the cause of the high temperature in many oil fields.) Where the water crosses a finer bed, the entrained globules of oil and bubbles of gas are withheld at the base of such a bed; thus, they accumulate at the anticline. This principle—that anticlines are the places where water of underground circulation escapes — was evolved by the writer in 1930.[1] John L. Rich, in a recent paper,[2] on other grounds comes to the same conclusion, that anticlines are the places where oil and gas from the water in the "carrier beds" accumulate. This geologist lays more stress on an escape of water through fissures.

The horizontal transportation of water is mainly accomplished in the coarse strata. When these contain coarser patches the paths of the water lead through them. Where the water leaves one coarser patch to find its way to the next, oil and gas are retained and in this way may accumulate in the coarser portions of the coarse-grained strata.

It has already been mentioned that along with the water which is stimulated by the percolation water of the highlands, some water also from the deeper strata, squeezed out by compacting pressure, has to discharge through the anticlinal folds. Not only are the argillaceous strata compressed, but compaction also takes place in the coarser, sandy strata, and it is perhaps the flow of water due to the compaction of the sandy, more than of the clayey, strata that causes the accumulation of oil in the anticlines. The clayey sediments are very easily compressed by the weight of overlying strata. This compaction may or may not be finished when the "structures" are formed. It may be supposed to occur as the weight of sediments increases.[3] This compaction of the argillaceous sediments is the cause of the oil particles being forced into the coarser layers with the water which is squeezed out of the clays.

The sands can be compacted in two ways. The grains may be crushed when they are submitted to a very high pressure, but such pressure can not be brought about until the thickness of overlying strata

[1] Jan Versluys, *Proc. Royal Acad.*, Vol. 33 (Amsterdam, 1930), pp. 990-95.

[2] John L. Rich, "Function of Carrier Beds in Long-Distance Migration of Oil," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 8 (August, 1931), pp. 917-20.

[3] Jan Versluys, "An Hypothesis Explaining Some of the Characteristics of Clay," *Proc. Royal Acad.*, Vol. 30 (Amsterdam, 1927), pp. 104-12.

is very great.[1] There is another way in which sands may be supposed to be compacted gradually. The water in the voids is a solution which tends to be in equilibrium with the minerals of the formation. Such equilibrium can not exist because at the points of contact of two grains the stress on account of the compacting pressure is greatest and this stress performs work when these corners give way, that is to say, when some substance is dissolved. So the total potential energy of the gravity action on the sediments decreases when the grains are dissolved or corroded at the points of greatest stress, and the same material is redeposited in the vicinity on the surface of the grains. The fact that the potential energy then decreases means that this phenomenon of dissolution and re-deposition will occur. In this way the centers of gravity of the grains approach one another and pore space decreases; consequently water is squeezed out. This compaction ultimately brings about cementation, which, as will be set forth later, may also have some bearing on the water conditions in the oil fields. The rate at which this compaction takes place depends on the amount of weight, but it is quite different from the compaction of argillaceous strata. In the latter, when part of the water has been squeezed out, an equilibrium may be established which is disturbed only when the pressure is changed. In sandy strata, however, the compaction by solution and recrystallization occurs slowly and it does not counterbalance the increase of the burden. Perhaps it would continue until the voids were entirely filled with secondary minerals, or until they were divided into disjointed compartments.

If the compaction of the argillaceous sediments, which occurs as the burden of overlying sediments increases, is not finished before the strata are folded, the principal result is the concentration of oil in the coarser strata.[2]

[1]Jan Versluys, "The Compacting Pressure of Sediments," *Proc. Royal Acad.*, Vol. 30 (Amsterdam, 1927), pp. 1004-09. E. Rieke's conception of the question was somewhat different; see "Zur Erniedrigung des Schmelzpunktes durch einseitigen Druck oder Zug," *Zentralblatt für Min., Geol., Pal.* (1912), p. 27.

[2]Various phenomena prove that in compaction of argillaceous strata there may be a certain equilibrium between the forces causing the compaction and those counteracting it. The former are the burden of the immersed overlying strata; the latter, in the writer's opinion, is adsorption of liquid at the surface of the clay particles. C. Terzaghi is of the opinion that it is due to elasticity of the clay minerals. Argillaceous strata may be further compacted, which was the cause of the subsidence of the Goose Creek field (see *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 887-89, and *Jour. Geol.*, Vol. 34 (1926), pp. 577-90), and they may expand under absorption of water when pressure is released. This is observed in various bore wells, and the shales are then said to heave (see W. F. Doherty, S. Gill, and C. P. Parsons, "Drilling Fluid Problems in the Gulf Coast," *Cementer*, Vol. 3, No. 4 (September, 1931), p. 1.

The compaction of the coarser strata, which proceeds at a slower rate but almost indefinitely, may be the main cause of the accumulation at the anticlines. In the later stages of compaction, the phenomenon of re-crystallization also takes place in the finer strata, and then again there is an excess of water, not only due to a decrease of pore space but also because new minerals may be formed with a smaller water content than the original clay minerals.[1]

The direction of the motion of water in alternating coarser and finer sediments after folding, if it is assumed that both finer and coarser sediments are still being compacted, is shown by the arrows in Figure 1.

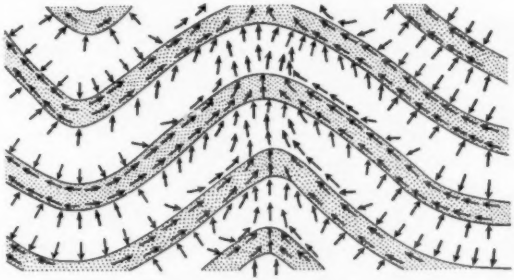

FIG. 1.—Dots, coarse grain; blank space, fine grain.

In this figure the coarse sands are supposed to be sheet sands. If they are more or less lenticular, the flow conditions are not materially altered.

The motion as shown in Figure 1 is generally accompanied and probably dominated by the general motion of subterranean water from the highlands to the lowlands which has been discussed in the previous pages. Such flow, however, has been omitted in Figure 1. This figure shows how water, oil, and gas are expelled from the fine layers into the coarse layers, and how the liquid then has to make its way upward across the coarse as well as the fine strata, particularly at the crests of the anticlines. Intermolecular forces, as previously described, will then retain the globules of oil and bubbles of gas, so that they accumulate under the fine-grained strata in the anticlines and domes. The fine-grained layers thus become the cap rocks of the oil.

Where the oil accumulates under the cap rock, the globules unite and gradually the pores of the coarse layer are filled with oil. An oil-filled layer of sand forms under the cap rock at the crest. This seals off

[1] J. V. Lewis, *Bull. Geol. Soc. Amer.*, Vol. 35 (1924), p. 567.

the upper part of the sand under the cap rock and no more water can pass, so that accumulation ceases. Then, however, accumulation must occur farther down the slope. As soon, however, as a continuous layer of oil is formed, this can move up dip due to buoyancy. There would be no other resistance than internal friction of oil, which approaches zero, as the motion becomes infinitely slow.

When a certain amount of oil in this way has accumulated in the structurally high portion of a coarse layer, the buoyancy tends to make the oil rise; consequently the oil exerts a pressure on the water in the cap rock, which equals the product of the difference in specific gravity and the height from the border of the edge water to the crest of the stratum. This pressure is counterbalanced by the intermolecular forces. These forces can only withstand a certain pressure, so that the height of the oil, although it may be great, can not increase indefinitely. It is quite probable that in some places the oil may penetrate the cap rock and perhaps all the oil may migrate to the next higher coarse sand. This condition has been discussed in another paper.[1]

When the coarse layer is filled with a continuous mass of oil, it may be assumed that the film of water covering the grains will disappear. Independent of the question whether, when the coarse layer is filled with a continuous mass of oil, there are still films of water covering the grains or not, the intermolecular energy would increase if the oil penetrated a finer layer, because if the oil replaces water in the finer layer, the interface, either of oil and mineral matter or of oil and water, must increase, resulting in a resistance opposed to movement of oil when penetrating finer layers.

Probably minute particles of water remain at the points of contact of the grains in loose sands, in the oil after its accumulation, because the grains are more easily wetted by water than by oil. The condition of the remaining water may be represented schematically by Figure 2. This condition corresponds with the "pendular condition"[2] of sand wetted with liquid. Then the liquid forms small pendular bodies at the points of contact of the grains. In the case of water and oil the pendular bodies are also water, while the surrounding medium is oil instead of gas.

Why oil, which wets the minerals better than water, does not accumulate is explained as follows. Soon after the globules of oil have been

[1] Jan Versluys, "Can Absence of Edge-Water Encroachment in Certain Oil Fields be Ascribed to Capillarity?," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 2 (February, 1931), p. 192.

[2] *Op. cit.*, p. 194.

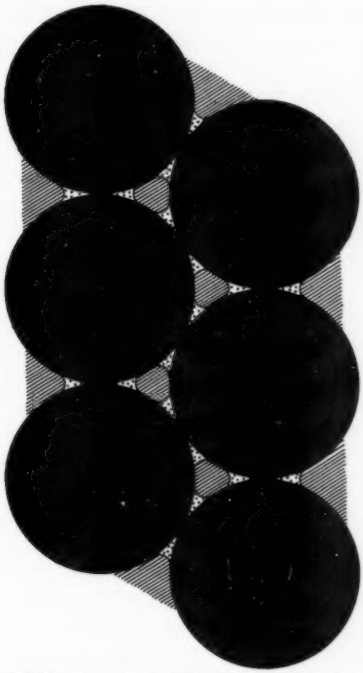

FIG. 2.—Solid black, mineral; diagonal lines, oil; dots, water.

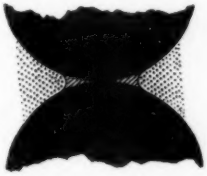

FIG. 3.—Solid black, mineral; diagonal lines, oil; dots, water.

formed, they adhere to the grains of the formation and gradually take the position shown in Figure 3. There are pendular bodies of oil in water. They remain at the spot and the formations contain erratic small bodies of pendular oil, which are not detected. The writer does not mean to

state that such oil exists;[1] he merely wishes to express the belief that all accumulated oil must have less affinity for the mineral grains than water, because otherwise it will not migrate. Moreover, oil with such a great affinity for the minerals tends to enter the finer strata if it can migrate at all.

The opinion that the flow of subterranean water, partly due to the undulations of the surface of the earth, and partly to compaction, is one of the factors involved in oil accumulation, is perhaps supported by the fact that many sands yield oil liberally without this being followed by a flow of water at a considerable rate. Not only do oil and gas occupy the coarse layers, but also they tend to fill the coarsest portions of such strata. The slow encroachment of some water may be accounted for by differential compaction, which may be explained as follows. Compaction of the coarser strata occurs through dissolution and recrystallization. The minerals, however, are not soluble in oil and gas; hence, these two processes are terminated after the pores are filled with oil. Therefore, after the accumulation of oil and gas, the compaction can continue only in the water-filled portion of the formation, so that here the pores become narrower than in the oil-filled portion of the sand if they were not from the beginning.

As far as the writer knows, there is no indisputable evidence of pendular water remaining in the oil after accumulation in loose sands, unless the water mentioned by Mills and Wells[2] may be regarded as such, which, however, is not quite definite. However that may be, the percentage of water in this way suspended amidst the oil is very small and it is not certain that it is entrained by the oil when this flows to a well, but even within such bodies dissolution and recrystallization may continue. However, the angles of the pore space around the point of contact of the grains gradually become less favorable for the suspension of water. The pendular water then must sink and segregate from the oil and unite with the water of the underlying fine-grained layer.

It is quite within the scope of the principles evolved in the preceding paragraphs that there should be exceptions to the rule that oil and gas accumulate at the crest of anticlinal folds. If the texture of a sand or sandstone is uneven, oil and gas may also accumulate in coarser

[1]Experiments performed by F. E. Bartell and F. L. Miller, "Degree of Wetting of Silica by Crude Petroleum," *Industrial and Engineering Chemistry*, Vol. 20 (1928), pp. 738-42, make it seem very improbable.

[2]R. Van A. Mills and R. C. Wells, "The Evaporation and Concentration of Waters Associated with Petroleum," *U. S. Geol. Survey Bull. 639* (1919), pp. 26-27.

patches in the syncline or on the flanks of the anticlines. This, therefore, is a consequence of the aversion of disseminated oil and gas to entering the smaller pores of a finer part of a layer, when the water flows longitudinally through the coarser layers. As far as the writer is aware, the earliest information on such a deviation from the anticlinal occurrence is given by C. A. Ashburner,[1] who observed in 1885 that several Pennsylvanian gas wells were in synclines. Little attention was given to Ashburner's statement, while other synclinal oil fields which were reported could easily be explained on the basis of the buoyancy theory. Since 1906 and 1907, discrepancies of the anticlinal occurrence of oil were found which could not be explained by buoyancy.

However, the principle that difference in the specific gravity is the sole agent causing the segregation of gas and oil at the top of an anticline was not discarded, and a new hypothesis was proposed to link these occurrences of oil and gas with the buoyancy theory. It was assumed that layers bearing oil at the flanks of the anticlines were but partly filled with water, and the beds with synclinal oil were free from water.[2]

The buoyancy theory implies that in ordinary water-filled sands oil and gas ascend to the crest, whereas oil descends to the syncline in dry strata and gathers at the top of the water in strata that are water-filled to a certain level.

As to the behavior of gas, it should be kept in mind, however, that there would then be only one possibility, that is, the gas would spread throughout the pores of the layer above the water level. This not being within the scope of the principles at that time, the supposition was ventured that the pores of the dry or unsaturated strata were filled with air under atmospheric pressure. This was supposed to be the condition even in strata which lay below sea-level.

Two distinct conceptions of the origin of dryness prevail.[3] One is the idea of "connate dryness." It was assumed that dry strata had been deposited by rivers in the coastal regions. Successive regressions

[1] *Science*, Vol. 5 (1885), p. 43, and Vol. 6 (1885), pp. 184-85.

[2] R. H. Johnson in 1921 tried to explain the occurrence of oil in the flanks without relying on the assumption of the strata being unsaturated. Johnson, in his paper, "Water Displacement in Oil and Gas Sands," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 65 (1921), pp. 498-500, assumed that an upward current of oil, gas, and water along the roof of an oil-bearing layer would induce a down-dip current along the floor which would cause the accumulation of oil and gas in the synclines.

[3] A fairly complete list of literature on dry or unsaturated strata is added to the writer's article, "The Problem of Dry or Unsaturated Strata," *Proc. Royal Acad.*, Vol. 34 (Amsterdam, 1931), pp. 591-97.

and transgressions of the sea had alternately exposed the territory to the atmosphere and submerged it, so that beds became dry and air-filled and were afterward covered with marine sediments. The advocates of this "connate dryness" believed that the air under atmospheric pressure prevented the penetration of water when the sand was submerged.

The second conception was that the so-called dry layers were water-filled when they became buried, but that they were desaturated subsequently. The process of desaturation was explained in three ways. One explanation was based on J. F. Kemp's theory that at a depth of about 600 meters, the strata lose their water content. Kemp's papers on this subject[1] are not very convincing. Moreover, water has since been encountered at much greater depths. The second explanation was that orogenic movements of the earth's crust and subsequent denudation had decreased the compacting pressure of sediments so that clays and shales could expand again. During the expansion, these fine-grained sediments would absorb water which was withdrawn from the coarser sands. These were in this way entirely or partly depleted. The third conception was that water of the deeper strata had been evaporated by circulating gases, principally methane (generated at depth), escaping to the surface, mainly through fissures.

Whatever assumption is made regarding the cause of the supposed dryness of the strata, the idea that dry strata occur at great depth implies the supposition that the overlying and the underlying strata are materially impervious. Otherwise, the dryness could not subsist. As has been stated, several geologists actually believe that only the coarser strata are aquifers, and that the shales and clayey strata are absolute barriers to the passage of liquids. The writer does not accept this theory; consequently, he does not accept the theory that beds containing only air at atmospheric pressure can exist at considerable depth. He admits that oil-bearing layers, which, after most of their oil has been tapped by exploitation, have their pores principally filled with gas under a much lower pressure than is inherent at their depth, may not always be immediately invaded by water, and that mines at a great depth may have a small influx of water, but such conditions could not last for the duration of geologic periods.[2]

Is there any evidence in favor of the theory that porous and easily permeable beds filled with air under a pressure of one atmosphere occur

[1] J. F. Kemp, "Waters, Meteoric and Magmatic," *Min. and Sci. Press*, Vol. 46 (1908), pp. 705-08, and "The Ground Waters," *Amer. Inst. Min. Eng. Bull. 76* (1913), pp. 604-24.

[2] The Berea sand, supposed to be dry, is Mississippian in age.

at great depth? Some advocates believe that it is proved by the fact that a borehole in such sands is not immediately filled with water, whereas the shallower sands when pierced by the drill show abundant water. This can be fully explained by a great resistance to the motion of water, because of the narrowness of the pores. Another argument would be that some sands which are supposed to be dry, take up water from the borehole with great avidity. This, however, proves only that sands with little resistance to motion of liquids or gases have been encountered, in which the pressure of the liquid is perhaps slightly lower than in the borehole. If the liquid in the borehole is a mud-laden water there may be a considerable excess of pressure in the hole.

Thus, these two lines of reasoning, cited as proofs that the sand is dry and contains only air under atmospheric pressure, do not prove this point at all. On the contrary, the former is in agreement with the writer's explanation of the occurrence of oil and gas outside the anticlines, which is explained hereafter.

Moreover, it has been argued that the fact that cores from the oil-bearing part of the so-called dry strata are not saturated with oil when they come to the surface, indicates that these strata are unsaturated and have low pressures. But it should not be forgotten that oil contains dissolved gas, which is liberated when pressure is diminished, so that no cores when brought to the surface are saturated with oil, the escaping gas having expelled part of the oil. In coarse sands this may be accomplished more quickly than in fine-grained sands, but the phenomenon must under all circumstances be perceptible. Thus, in the writer's opinion, no proofs have been supplied of the dryness of certain sands and of the low pressure prevailing in them.

The only observation which has led to the conclusion that certain beds are dry is that oil therein occurs outside the anticlinal regions. As for the remainder, the conclusion is merely based on hypotheses. These hypotheses concern the way in which the supposed state of dryness has arisen and include the old theory that oil rises to the anticlines as a consequence of its low specific weight,—and subconsciously two other conditions have been assumed: (1) that such beds are uniformly porous, and (2) that they are overlain and underlain by materially impermeable layers.

The occurrence of oil and gas in the synclines may well be explained as a consequence of differences of the cross sections of the pores in the different portions of the sand. If this explanation is adopted, the im-

probable theory of the existence of strata containing air under atmospheric pressure at great depth can be abandoned.

While the advocates of the theory of strata being partly filled with oil and water and partly with air under atmospheric pressure have failed to produce any evidence in favor of this theory, some evidence against this theory is available. The wells in synclinal oil accumulations flow naturally. This means that such oil contains gas which is dissolved under a considerable pressure. If such oil were stored in the deeper parts of a porous bed containing only low-pressure air, the oil would first rise in the form of a foam and gradually percolate slowly down to the synclines, or to the top of the water filling the lower part of the bed. The gas would then spread evenly through the higher parts of the bed, up to the crests of the anticlines. Moreover, in some descriptions of synclinal oil occurrences, it is stated that there was high-pressure gas above the oil, though the authors of such papers asserted that the anticlinal portions are filled with air under low pressure. This is not possible if the bed is porous throughout. The writer's conception[1] is that oil and gas accumulate at the anticline if the bed may be considered uniformly porous, but if there are finer and coarser portions in a sand or sandstone, oil and gas may accumulate in the coarser portions, independent of their position in relation to the folding of the layers. The pores of the finer portions then are water filled.

Besides oil occurring in the syncline, in uniform layers there should be sufficient gas to fill the higher parts of the anticline. This has been pointed out by the writer in a previous paper.[2] It appears from the descriptions of several fields that this actually may occur. There are, however, theoretical grounds for believing that the total height to which a layer can be gas-filled is limited, as previously explained. Even at a considerable depth, the prevailing pressure is not high enough to compress the gas to a specific weight which approaches that of water. Therefore, when at the bottom of the gas-filled part of a layer the pressure is equal to the pressure inherent at the given depth, the pressure of the gas at the top of the layer must be considerably lower than that of the water in the contiguous overlying finer strata. This difference must be outweighed by capillary forces which, however, are limited. Consequently, if the height of a gas accumulation exceeds a certain limit, it penetrates the cap rock and rises to the next higher coarse layer.

[1] Jan Versluys, *op. cit.*, p. 596.

[2] *Idem*, "Synclinal Oil and Unsaturated Strata," *Proc. Royal Acad.*, Vol. 31 (Amsterdam, 1928), pp. 1086-90.

Several accumulations of oil which are considered synclinal seem to be situated in small shallow secondary synclines in anticlines, or in the synclinal folds in the flanks of anticlines or domes; hence such oil occurrences can also be called anticlinal. There are oil fields, at the outcropping edges of sands, the top parts of which are sealed with asphalt. If such a layer is tortuous, the sloping synclines may be oil-bearing, but this has little to do with the occurrence of oil in real synclinal troughs. Perhaps the occurrences of true synclinal oil are not so numerous as might be inferred from the literature; however, most exploration has been based on the anticlinal theory, and little exploration has been done in synclines. It seems that in future the synclines will receive more attention. W. A. Ver Wiebe[1] writes that "exaggerated importance is attached to anticlines as the cause for oil accumulation," and C. Croneis,[2] in studying the possibilities of oil occurrence in Arkansas, gave proper attention to the synclinal regions.

Regarding the synclinal oil occurrences, the writer believes that the existence of unsaturated strata at depth, overlain by water-filled beds, is very improbable and that no actual proof for their existence has been furnished. The relative hypothesis has been proposed only to link the observation of synclinal occurrence of oil with the buoyancy theory. This phenomenon, however, can be explained on the assumption that formations which bear oil outside the anticlines have variable texture. The main cause of the accumulation of oil or gas in the anticlines as well as in the synclines and on the flanks does not, therefore, seem to be buoyancy, but may be more logically attributed to the flow of water together with the aversion of oil and gas to leaving coarser strata or coarser portions of the strata when they have once entered them. Thus the occurrence of oil and gas would make the writer's conception of the cause of their accumulation more plausible.

Except for the cause of accumulation at the anticlines, the writer's conception agrees with the hydraulic theory of Munn and Rich.

There is another fact which seems to add to the proof for the correctness of the foregoing statements. Dorsey Hager[3] points out that the contact of oil and water on an anticline is an inclined plane and that

[1]W. A. Ver Wiebe, *Oil Fields in the United States* (McGraw-Hill Book Company, New York, 1930).

[2]C. Croneis, "Geology of the Arkansas Paleozoic Area," *Arkansas Geol. Survey Bull. 3* (1930).

[3]Dorsey Hager, *Practical Oil Geology*, 3rd ed. (McGraw-Hill Book Company, New York, 1919), p. 167.

on the steeper side of the fold the water rises higher than on the gentler side, and that oil extends farther down the plunges than would normally be expected. No sources of literature are mentioned, but the observation is said to be recent.

If the sand were of the same texture throughout and a static equilibrium prevailed, a cross section of the fold would be depicted by Figure 4, whereas, according to the idea that the plane of contact is inclined, the condition would be shown by Figure 5, in which the portion shown

FIG. 4

FIG. 5

in black denotes the oil-bearing portion of the layer. This conception seems to be derived from C. H. Beal's[1] description of the Cushing field.

Very shortly before Beal, John L. Rich[2] described similar conditions in fields in the Birds Quadrangle, Illinois. Rich gave an explanation of the phenomenon, which, in the writer's opinion, is the most probable and which quite agrees with the theoretical views set forth in the foregoing pages. Rich was of the opinion that the inclination of the surface of contact is due to differences of pore sizes in the sand, or in other words, capillarity is an important factor in the shape of oil accumulations. The correctness of Rich's opinion is supported by the fact that the sand in which he observed an inclined plane of contact between oil and water, also contained smaller lenticular oil accumulations. C. H. Beal,[3] in his description of the Cushing field, remarks that the oil-bearing sand was not of a uniform texture.

M. R. Daly[4] ascribed the deviation of the surface of contact between oil and gas in the Cushing field from a horizontal plane to the differentials of pressure which cause the motion of the water in the sand. He considered these differentials a consequence of diastrophic pressure.

[1]C. H. Beal, "Geologic Structure in the Cushing Oil and Gas Field, Oklahoma, and Its Relation to the Oil, Gas and Water," *U. S. Geol. Survey Bull. 658* (1917).

[2]John L. Rich, "Oil and Gas in the Birds Quadrangle," *Illinois Geol. Survey Bull. 33* (1916), pp. 105-45.

[3]C. H. Beal, *op. cit.*, p. 39.

[4]M. R. Daly, "Water Surfaces in the Oil Fields," *Trans. Amer. Inst. Min. Eng.*, Vol. 59 (1918), pp. 557-63.

The writer believes that such pressures, which in his opinion are caused mainly by differences of altitude at the surface, may have some bearing on the shape of the plane of contact, but it seems to him that the influence of capillarity is preponderant. The fact that in certain anticlinal oil fields the productive area is sagged, independent of the anticline, may in the same way as the previously described phenomena be attributed to differences of texture, if faults can not account for it.

In some oil fields a thin shale parting separates — at least in a limited area — an oil-bearing top sand from a water-bearing bottom sand. J. S. Ross[1] recently described such a condition, but he mentioned that the bottom sand was calcareous and argillaceous. Perhaps in many such places it is not exactly the thin parting layer which separates oil from water, but the different conditions under and above this parting, caused by a difference of texture. Thin layers may be broken so that they could hardly establish a permanent partition.

It might be profitable to study all phenomena, such as irregularity of the boundaries of anticlinal oil fields and inclination of the plane of contact of oil and water, from the standpoint that variation of texture is an important factor in all matters of oil and gas accumulation. When such phenomena are encountered, they may indicate that the texture of the formation is irregular; hence accumulations are not of necessity limited to the anticline.

The following conclusions are drawn from the preceding pages.

1. The most important factors in accumulation of oil and gas are as follows: (1) the intermolecular forces which cause an aversion of the disseminated oil and gas, as well as of the accumulated oil and gas, to leave the coarser strata or the coarser portions of such strata; (2) the subterranean flow of water from the highlands longitudinally through the coarser beds toward the lowlands and the ascent of this water in the lowlands, mainly on the anticlines; (3) the discharge of the excess of water at depth, caused by compaction of strata, this discharge following the same paths as the ascending water of the flow mentioned under (2); (4) compaction of argillaceous strata which forces the connate water contained by them, together with disseminated oil and gas, into the coarser beds.

2. The most important function to be attributed to buoyancy is to achieve segregation of oil as well as gas during and after the accumulation by the subterranean flows (see 1).

[1] J. S. Ross, "Engineering Report of Cotton Valley Field, Webster Parish, Louisiana," *U. S. Bur. Mines Tech. Paper 504* (1931).

3. Dry or unsaturated strata do not exist at depth.

4. The tardiness of edge-water encroachment, during exploitation of certain fields which yield oil and gas readily, may be attributed partly to the differences of texture which influence accumulation of the oil and gas, and partly to the persistence of compaction and cementation in the edge water while they are discontinued where oil or gas fills the pores.

5. Synclinal oil and gas can be expected only in sands with tardy edge-water encroachment and an irregular shape of productive areas, unless the irregularity is caused by dislocations.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 9 (SEPTEMBER, 1932), PP. 943-944

GEOLOGICAL NOTES

PROBABLE AGE OF APTYCHUS-BEARING FORMATIONS OF CUBA

Organic limestones and shales, many of them petroliferous, which contain ammonite aptychi, occur in the upper portion of the Jurassic series in the mountains northwest of Artemisa in Pinar del Rio Province. Numerous exposures of similar aptychus-bearing rocks are found within areas of Cretaceous rocks throughout the entire island. For the most part these exposures are too small to permit their appearance on a small scale map, but they do indicate that these organic and petroliferous rocks are present below most of the younger sediments.[1]

Marjorie O'Connell has published photographs and descriptions of these aptychi.[2] She states that they were taken from shales which appear to belong to the upper portion of the Jurassic series of eastern Pinar del Rio Province. Her opinion is that they are of either late Jurassic or early Cretaceous age with strong paleontological evidence pointing to the latter conclusion.

The writer has discussed the age of these fossils with several paleontologists who are familiar with the ammonites of both Europe and Mexico. The general attitude on this subject is well expressed in a letter from Gayle Scott in which the following is stated:

> ...we have talked over the problem a number of times since listening to your...paper.[3] At that time, I recall, some one was taking the position that these Aptychus beds were *Upper* Cretaceous. I could not subscribe to this idea at all. Aptychus does occur in the Upper Cretaceous in a few places, for example Japan, but they are apparently the aptychi of *Scaphites* and not like those of Cuba.
>
> To me the Cuba forms are for the most part between the well known Jurassic and Cretaceous types. Under the circumstances I think that they are not particularly conclusive, and if I had good evidence for thinking the rocks of Jurassic age I should certainly stick to that idea until some conclusive evidence to the contrary is brought forward.

[1] J. Whitney Lewis, "Geology of Cuba," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 6 (June, 1932), pp. 533-55.

[2] Marjorie O'Connell, "New Species of Ammonite Opercula from the Mesozoic Rocks of Cuba," *Amer. Museum Novitates*, No. 28 (1921).

[3] J. Whitney Lewis, *op. cit.*

The fact that no occurrences of aptychi in the Cretaceous rocks of either the Antilles or the mainland of the Americas have been reported to date is also important. The evidence now available seems to point strongly to the conclusion that these fossils are late Jurassic in age.

J. WHITNEY LEWIS

1432 VICTORIA AVENUE
LOS ANGELES, CALIFORNIA
July 20, 1932

HIGH ISLAND DOME, GALVESTON COUNTY, TEXAS

CORRECTION

In the July *Bulletin*, page 701, in M. T. Halbouty's note, "High Island Dome, Galveston County, Texas," the sentence beginning in the eighth line of the second paragraph should read: "The Yount-Lee Oil Company's Cade No. *22*, located 740 feet W. of E. line," et cetera.

REGIONAL STRUCTURE OF CRETACEOUS ON EDWARDS PLATEAU OF SOUTHWEST TEXAS

CORRECTION

In the July *Bulletin*, page 699, in Lon D. Cartwright's article, "Regional Structure of Cretaceous on Edwards Plateau of Southwest Texas," the last word in the first paragraph should be *plateau* instead of platform.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 9 (SEPTEMBER, 1932), PP. 945-951

REVIEWS AND NEW PUBLICATIONS

Petroleum Development and Technology, 1932. By the Petroleum Division, American Institute of Mining and Metallurgical Engineers, Inc., 29 West 39th Street, New York, N. Y. (1932). 506 pp., illus., cloth. Price, $5.00.

Petroleum Development and Technology, 1932, is composed of 50 papers and accompanying discussions presented at the meetings of the A. I. M. E. Petroleum Division at Houston, October 2 and 3, 1931, and at New York, February 15-18, 1932, presented in six chapters.

Chapter I. Stabilization.—A program of stabilizing the entire mineral industry should be based on the general principle of conservation, but at the present time there is no adequate conception of the true meaning of conservation. An adequate plan can be formulated only after a long, hard course of effort and study by men familiar with the mineral industry.

There must be a change in the legal concept of ownership, from that of capture to ownership in place, permitting orderly development, and equitable distribution of oil and gas to the benefit of all producers in a common pool.

Chapter II. Economics.—Losses in the oil industry have been sustained during the past year due to loss of foreign markets, decreased domestic consumption, and the uneconomic use of excess refining and distributing capacity. Important advances have been made in the producing branch, through curtailment. While proration has built up a large invisible inventory which has affected price, and has had other ill effects, both economic and political, yet it has established the principle of ratable taking—an important step toward unit operation—and has increased operating efficiency.

Chapter III. Production, domestic and foreign.—Due to conditions, wildcatting was at a minimum in the United States, and very few important discoveries were made. East Texas contributed the greatest amount of activity and new production. Overproduction of flush fields, falling prices, and the decline of old fields characterized the year.

Venezuela experienced its first break in production since 1920, due largely to curtailment, proved fields in Russia are rapidly being drained, and other countries experienced similar declines. Very little exploratory drilling was done anywhere, with no important new discoveries.

Chapter IV. Petroleum Engineering.—Petroleum engineering in 1931 was concerned mainly in finding ways and means of reducing operating investments and expenses. During the year, important investigations were made in the fields of bottom-hole pressures, conservation of gas energy, gas-oil ratios, and more efficient use of tubing.

Chapter V. Engineering Research.—Papers are presented discussing the flow of oil and gas through porous media, computing pressure drop in the pipe of flowing oil wells, experimental studies of pressure conditions within the oil reservoir rock in the vicinity of a high-pressure producing well, experiments

on the behavior of natural gas in an oil-sand reservoir and the flow of drilling mud.

Chapter VI. Refining.—In the refining branch of the industry, 1931 has seen progress in the development of new products and the adaptation of petroleum derivatives to new uses. The use of anti-knock gasoline has increased, with the introduction of the term "octane number" as a measure of anti-knock properties. It has become necessary to crack an increasing percentage of paraffine-base crudes, to produce gasoline with a sufficiently high octane number.

ROBERT H. DOTT

TULSA, OKLAHOMA
July 11, 1932

Jahrbuch des Deutschen Nationalen Komitees für die Internationalen Bohrkongresse (Yearbook of the German National Committee for the International Drilling Congress), Band II (1932). 360 pp., 71 illus. Laubsch and Everth, Berlin, S. W. 68.

The *Yearbook* contains the following papers.

1. A. Bentz, "The Different Oil Horizons of Northern Germany, Their Primary or Secondary Origin," pages 21-109, and 22 maps and figures
2. E. H. W. Zaeringer, "The Importance of Drilling Technique in the Freezing Method of Sinking Shafts together with Exposition of the Method of Execution of the Freezing Process," pages 111-28
3. H. Reich, "What Rôle Does Geophysics Play in Drilling for Oil," pages 129-58
4. W. Halder, "The Problem of Drilling Mud," pages 159-90
5. W. Halder, "A New Depth Record, Jardin No. 35," pages 191-204
6. W. Halder, "Technical Data in Regard to Three Very Deep Wells," pages 205-14
7. W. Kauenhowen, "The East Texas Oil Field, Studies of the Present-Day Greatest Oil Field in the World," pages 215-60, and 34 illustrations
8. E. Fulda, "Mining Laws in the Oil Regions of the World," pages 261-90
9. A. Hoffman, "Progress in the Production of Oil," pages 291-314
10. Summary, English abstracts of the papers, pages 317-27
11. Résumé, French abstracts of the papers, pages 328-39

Two of the papers may be of interest to American geologists: Bentz gives one of the best and most up-to-date descriptions available of the occurrence of oil in North Germany; in his detailed consideration of the origin of the oil deposits, he conforms to present German fashion and concludes that oil in general is secondary and has come from Permian beds below the salt series. Those conclusions are vigorously opposed by Stutzer and Kauenhowen in the discussion. Students of oil and of geological and technological German should find Kauenhowen's paper on East Texas valuable for practice in translation, for it covers familiar subject matter and the paper also gives an interesting all-around picture of the field and drilling and production practice there.

American geophysicists will be interested in Kauenhowen's statement that his torsion-balance work for the Ohio Oil Company was of considerable value to the company in the selection of favorably placed acreage in the East Texas field and in Reich's presentation of the discovery torsion-balance map of the Sugarland dome.

The volume may be obtained from the Deutsche Nationale Komitee für die Internationalen Bohrkongressen, Berlin, S. W. 68, Alte Jacobstrasse 18-19.

DONALD C. BARTON

HOUSTON, TEXAS
July 18, 1932

Das Erdöl (Petroleum). By C. ENGLER and H. HÖFER. 2nd ed. Edited by J. Tausz. Vol. 3, Pt. I, *Gewinnung des Erdöls* (Production of Petroleum), contains "Gewinnung des Erdöls durch Bohren" (Production of Petroleum by Drilling), by K. Glinz, and "Gewinnung des Erdöls durch Schachtbau" (Production of Petroleum by Mining), by G. Schneiders. (S. Hirzel, Leipzig, Germany, 1932.) xii + 262 pp., 202 figs., 4 tables. Lexikon-Format Boschiert, RM. 38; Leinen, RM. 40.

In the first part of the volume, "Gewinnung des Erdöls durch Bohren," K. Glinz describes the various drilling systems and production methods. Particular attention has been given to a discussion of the different types of drilling machines, while the production methods, particularly the gas and water-drive methods, have been treated in a more cursory way.

The book is of interest to the American petroleum engineer, as it describes certain drilling methods and practices peculiar to the European oil fields, for example the method of *Seilschlagbohren*, a combination of the percussion method and continuous mud circulation. This method has been very popular in Europe, but is giving way more and more to the modern rotary rig.

The author has a tendency to generalize, which may be somewhat misleading, for example in the statement (p. 132) that choking reduces the gas-oil ratio (the contrary is often true), or in the summary of his discussion on the various production methods (p. 163), where he states that natural flow and pumping will produce 20 per cent of the oil originally contained in the sand, gas lift 40 per cent, gas and water drive 70 per cent, and that 20 per cent of the remaining 30 per cent can be obtained through mining.

The book is well illustrated and contains much valuable information.

In the second part, "Die Gewinnung des Erdöls durch Schachtbau" (Recovery of Oil by Mining), G. Schneiders describes oil mines with much valuable information about the sinking and lining of the shaft and the driving of drifts in the oil sands or in the adjoining formations, and about methods of overcoming difficulties caused by gas. The discussions of the author are especially valuable, because he was, during the war, in charge of the operations of the Pechelbronn oil mine, and has also had practical experience in oil mining in Wietze, Germany.

The author does not enter into any detailed discussion of the results of mining, nor does he give any cost figures. For a more detailed description of oil mining he refers to his book, *Die Gewinnung von Erdöl* (Production of Petroleum).

R. W. BRAUCHLI

OKLAHOMA CITY, OKLAHOMA
July 8, 1932

"Vers la recherche de nouveaux champs pétrolifères" (In Search of New Oil Fields). By STANISLAS ZUBER. *Mémoire présenté au Congrès International des Mines, de la Métallurgie et de la Géologie appliquée*, 6e session, Liége, 22-28 Juin, 1930 (H. Vaillant-Carmanne, S. A., Imp. de l'Académie, Place St.-Michel; 1931) pp. 215-19.

In this short paper, the author emphasizes the value of the practical application of paleogeographic methods in search for new oil fields.

Zuber first gives briefly his ideas concerning the origin and accumulation of oil which, even though not acceptable to everybody, form the fundamental principles which convince him of the practical value of paleogeographic studies. His theory, which has been defended in several previous publications, is based on investigations in the upper Tertiary sediments of Poland, Roumania, Albania, and Italy. Whether it will satisfactorily explain the oil resources of these countries or not, I can not judge. He firmly believes that oil originated from vegetable detritus accumulated in tropical deltas, marine lagoons, or reefs. Based on this conception, all petroliferous beds are regarded as primary in the strictest sense of the word. The accumulation and immediate preservation of the original material are thought to be a function of conditions of sedimentation, and the petroliferous diagenesis a function of the salinity of the mother-rock in which the transformation of the organic detritus took place. He believes that the persistence of the lithologic facies of petroliferous series excludes any possibility of vertical migration, and thinks that horizontal migration could develop only under exceptional conditions, even in the case of subsequent tectonic changes affecting the strata.

With these fundamental principles in mind, Zuber arrives at the conclusion that an analysis of the horizontal development of stratigraphic series, and the deciphering of diastrophic events recorded by changed conditions of sedimentation, will lead to the discovery of productive beds. Petroliferous zones are connected with movements in the earth crust. The discovery of oil territory depends, therefore, on the search for petroliferous zones in regions of tectonic movements. The author stresses the idea that the distribution of oil depends on the progressive sequence of sedimentation and folding in the region of mountain building. Oil is of sedimentary origin and the preservation or destruction of oil accumulation is dependent on type and degree of folding.

Paleogeographic analysis of the sediments will throw light on the changes of the petrographic facies, the variation of thickness of strata, as well as the direction in which changes of facies and thickness of beds take place. It will help to locate deltas, lagoons, the presence and position of strand lines, transgressions, disconformities, and unconformities. It furnishes information concerning time and magnitude of tectonic movements. Summarized in a few words, paleogeographic analysis will help to decipher the geologic history of the region under investigation.

Zuber's paper deals with a timely subject. Paleogeographic methods will play a prominent part in the discovery of new oil resources. The reviewer mentions only the strand-line oil field of East Texas, and the oil accumulation

in Pennsylvanian beds of the greater Seminole oil field to indicate the types of oil fields that paleogeographic methods will help to discover.

CHARLES RYNIKER

TULSA, OKLAHOMA
August 6, 1932

Physics, Vol. 2, No. 3 (March, 1932). The American Physical Society (W. L. Severinghaus, Columbia University, New York City). Annual subscription, $5.00 to members, $7.00 to non-members.

This issue of 98 pages was devoted to geophysics. There are nine papers, one on the electrical method, three related to gravity methods and instruments, two on geothermal methods, and three on seismology.

The paper on "Aspects of Electrical Prospecting Applied in Locating Oil Structures," by Peters and Bordeen, takes up the general problems of electrical prospecting as well as some of the limitations of the present methods. The mathematics of some of the problems are given. The authors do not believe that present methods will disclose information of geological value at depths greater than 2,000 feet.

Hartley's article describes a new type of spring balance by which, with the use of a heavy suspending spring, a fine adjusting spring, and a large optical magnification, he can measure gravity to one part in a million with considerable hope of increasing the sensitivity four or five times. Some of the inherent difficulties are discussed.

Slotnick gives a chart method of determining the gradient and curvature from torsion-balance readings without resorting to cumbersome calculations.

Zirbel gives some data of interest to the torsion-balance expert on the use of heat treatment in eliminating the time drift of loaded filaments. The method will also eliminate the shift in equilibrium position with temperature.

Van Orstrand's article gives some excellent examples of the connection between isogeothermal surfaces and structure, both subsurface and surface. He gives also the mathematical treatment for such problems and discusses the cause of regional variations in the isotherms.

Ingersoll reports on his temperature measurements in the deep copper mines of northern Michigan. He describes the type of thermometer used and method of taking readings. His analysis of the data, which were taken in an attempt to arrive at the thermal history of the area, points to a time of 30,000 years since the last glacial epoch.

Leet and Ewing's paper "The Determination of the Velocities of Elastic Waves in Granite" gives a mean longitudinal velocity of 16,530 feet per second and a transverse velocity of 8,150 feet per second for measurements in Massachusetts and Rhode Island. From these velocities, the elastic constants are computed. Comparison is made between their results and values previously found by laboratory methods. Specimen records and time-distance graphs are shown.

McCollum and Snell have a paper which discusses the difference between sound velocities for travel paths normal to and parallel with the bedding planes.

They show how this velocity asymmetry may be used for mapping structure.

A paper by H. A. Wilson shows how the actual motion of the ground may be calculated from records taken with a mechanical seismograph. He includes in his analysis cases where the instrument has zero and critical damping, also where the natural period has several different values.

B. B. WEATHERBY

TULSA, OKLAHOMA
August 15, 1932

RECENT PUBLICATIONS

AUSTRALIA

"Prospecting for Oil in Australia and New Guinea," by E. C. Andrews. *Econ. Geol.*, Vol. 27, No. 4 and No. 5 (July and August, 1932), pp. 365-79 and 471-86.

CALIFORNIA

"Commercial Oil and Gas Production in Northern California Not Far Off," by Walter Stalder. *Petrol. World* (Los Angeles), Vol. 29, No. 7 (July, 1932), pp. 13-16, 60; 7 figs.

"Migration of Injected Gas Through Oil and Gas Sands of California," by H. C. Miller. *U. S. Bur. Mines Rept. of Investigations 3177* (Washington, D. C., June, 1932). 29 pp. (mimeographed), 9 figs., 9 tables.

CANADA

Geol. Survey of Canada Summary Rept., 1931, Part A (Ottawa, Canada, 1932). 120 pp., 8 figs., 1 pl. Contains among other papers, "Oil Possibilities Between Soda Creek and Quesnel, Cariboo District," by W. E. Cockfield, pp. 58-65; and "Borings for Water, Oil, and Gas in British Columbia," by W. A. Johnston, p. 110.

FRANCE

"Le pétrole dans les possessions françaises" (Petroleum in French Possessions), by Léon Bertrand. *Ann. de l'Office Nat. des Comb. Liq.* (Paris), Vol. 7, No. 2 (March-April, 1932), pp. 195-216.

GENERAL

"Petroleum Development and Technology, 1932," by the Petroleum Division. *Trans. Amer. Inst. Min. Met. Eng.* (New York, 1932). 506 pp., illus., cloth. Price, $5.00.

"Present Distribution and Thickness of Paleozoic Systems," by Walter A. Ver Wiebe. *Bull. Geol. Soc. Amer.*, Vol. 43, No. 2 (June, 1932), pp. 495-540; 7 figs.

"Reservoir and Bottom-Hole Producing Pressures as a Basis of Proration," by C. V. Millikan. *Oil Weekly* (August 8, 1932), pp. 34-36.

"The Rôle of Engineering in Petroleum Exploitation," by Stanley Herold. *Oil Weekly* (July 25, 1932), pp. 33-34.

"Die Bildung des Erdöls und seiner Lagerstätten im Lichten migrationsverneinder Tatsachen" (The Formation of Petroleum and its Deposits in the Light of Facts Denying Migration), by Stanislas Zuber. *Inter. Zeits. f. Bohrtech. Erdölbergbau, und Geol.* (Vienna), Vol. 40, No. 13-15, July 1, 15, August 1, 1932), pp. 112-14; 122-26; 134-39.

GEOPHYSICS

Prospecting and Exploration, by R. C. Matson. Michigan College of Mining and Technology, Houghton, Michigan (1932). 45 pp., 43 figs. 8 3/8 × 10 7/8 inches. Paper cover. Presentation of principles and practices for readers without technical training; for Freshman course in mining. Price, $0.60.

ITALY

Possibilità petrolifere nel territorio di Tramutola in Basilicata (Petroleum Possibilities near Tramutola in Basilicata), by Guido Bonarelli. Reprinted by the National Committee on Geology (Italy) from *Giornale di Geologia, Annali del R. Museo geologico di Bologna*, Vol 7 (1932). 24 pp., 1 map, 1 plate of geologic sections.

LOUISIANA

"Zwolle Expects Deeper Pays Over Large Area—Glen Rose of Trinity Now Being Prospected," by H. D. Easton. *Oil Weekly* (August 8, 1932), pp. 30-32; 1 map.

OKLAHOMA

"Oklahoma Experiment Promises Success in Water Flooding," by Floyd Swindell. *Oil Weekly* (July 25, 1932), pp. 36-37; 3 figs.

PENNSYLVANIA

Geologic Map of Pennsylvania, prepared and edited by George W. Stose and O. A. Ljungstedt. *Pennsylvania Topog. and Geol. Survey, 1931* (Bur. of Publications, Harrisburg, 1932). In coöperation with *U. S. Geol. Survey*. Scale, 1 inch equals 6 miles. Legend of sedimentary and igneous rocks in colors. 3 geologic sections. One sheet, 61½ × 40 inches. Price, $1.50.

"Subsurface Structure of the Northern Pennsylvania and Southern New York Natural Gas Fields," by J. French Robinson, Verner Jones, and J. Gaddess. *Oil and Gas Jour.* (August 11, 1932), pp. 10-12; 4 figs.

"Geology and Coal, Oil, and Gas Resources of the New Kensington Quadrangle, Pennsylvania," by G. B. Richardson. *U. S. Geol. Survey Bull. 829* (1932). viii + 102 pp., 9 pls. (incl. 4 maps), 6 figs. Price, $0.40.

SWEDEN

"Erdölführende Schichten im Kambro-Silur von Västergotland" (Oil-Bearing Beds in the Cambro-Silurian of Västergotland), by R. Schreiter. *Petrol. Zeits.* (Berlin), Vol. 28, No. 27 (July 6, 1932), pp. 1-5; 6 figs.

TEXAS

"The East Texas Field—What It Has Done and What to Expect of It," by J. S. Hudnall. *Oil Weekly* (July 25, 1932), pp. 25-30; 2 maps.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 9 (SEPTEMBER, 1932), PP. 952-953

THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to J. P. D. Hull, business manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

FOR ACTIVE MEMBERSHIP

William Theodore Born, Bloomfield, N. J.
B. B. Weatherby, Andrew Gilmour, E. DeGolyer

Virgil August Brill, McCamey, Tex.
J. Ben Carsey, E. H. Sellards, Vaughn C. Maley

Joseph Zaba, Houston, Tex.
Melbert E. Schwarz, J. M. Vetter, Wallace E. Pratt

FOR ASSOCIATE MEMBERSHIP

James Edward Gunn, Houston, Tex.
Dart Wantland, C. A. Heiland, W. F. Henniger

Henry C. Cortes, Lake Charles, La.
Lee Hager, Alexander Deussen, L. P. Teas

SUPPLEMENTARY MEMBERSHIP LIST, SEPTEMBER 1, 1932

Members 18
||Associates 10

Total additions since publication of list in March *Bulletin* 28

Albrecht, Helmuth, Burback-Kaliwerke Aktiengesellschaft, Kaiser-Otto-Ring 25, Magdeburg, Germany

Anderson, Carl C., Box 2025, Amarillo, Tex.

Andrau, E. W. K., Shell Petroleum Corp., Houston, Tex.

||Black, J. P., Gulf Production Co., Drawer C, Houston, Tex.

Braendlin, Emil, P. O. Box 57, Miri, Sarawak via Singapore, Borneo.

||Brankstone, H. R., 1256 McNeilly Ave., Pittsburgh, Pa.

Briggs, Robert C., Jr., 207 Plaza Apartment Hotel, Houston, Tex.

Butt, William H., Apartado 10, Matanzas, Cuba.

Campbell, Keir A., 1077-A Broadway, San Francisco, Calif.

Charlton, Frances, Dept. of Paleontology, University of California, Berkeley, Calif.

Coleman, Don P., 3223 E. English, Wichita, Kan.
||Dinsmoor, Carlton G., Moran, Tex.
||Eckenwiler, Cleo W., 226 E. Fifth, Tulsa, Okla.
Esary, Ralph E., 925 Hunter Ave., Bloomington, Ind.
Hardison, G. P., 616 So. 6th, Clinton, Okla.
Koenig, Ralph, Box 548, Carlsbad, N. Mex.
McAuliffe, G. C., Drawer 1346, Monroe, La.
||Mechling, George W., 1995 Park Ave., Lincoln, Neb.
||Munyan, A. C., 267 E. High St., Lexington, Ky.
Murayama, K., No. 211, Koenji, Suginami-machi, near Tokyo, Japan.
Pittman, C. V. A., 1311 Republic Bank Bldg., Dallas, Tex.
||Porter, John L., 181 Claremont St., Long Beach, Calif.
||Riggs, Calvin H., Box 34, Muskegon, Mich.
Shaub, Benjamin M., 21 Massasoit, Northampton, Mass.
Talbott, W. G., 732 N. E. 21st St., Oklahoma City, Okla.
Ten Eyck, Warren E., 4041 Pacific Ave., Long Beach, Calif.
Thomas, Harold S., 2841 W. 21st St., Oklahoma City, Okla.
Uyemura, Kimio, Honchō-dōri Gochōme, Nakano-machi, near Tokyo, Japan.
Wanless, H. R., 126 Natural History Bldg., Urbana, Ill.
||Wedel, Arthur, Box 327, Mt. Pleasant, Tex.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 9 (SEPTEMBER, 1932), PP. 954-956

AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

CHESTER W. WASHBURNE, of New York, has finished a tour of lectures on normal faulting delivered at Princeton University, University of Cincinnati, Leland Stanford Jr. University, and the state universities of Louisiana, Texas, California, and Oregon. The University of Oregon conferred on him the honorary degree of Doctor of Science.

JOHN N. TROXELL, subsurface geologist for The Texas Company, has been transferred from the Oklahoma-Kansas division at Tulsa to the South Texas division of the company at Houston.

J. L. ANDERSON has accepted a position as assistant geologist for the Tropical Oil Company, at El Centro, Colombia, South America.

PAUL L. VAUDOIT, chief exploitation engineer, Gulf Coast Division, Shell Petroleum Corporation, left for the offices of the Shell Company, The Hague, Holland, the latter part of July. He will be there about six months.

C. A. HEILAND, Colorado School of Mines, Golden, and W. E. PUGH, geologist for the Plains Exploration Company, Denver, Colorado, are co-authors of a paper entitled "Theory and Experiments Concerning a New Compensated Magnetometer System." This paper was presented at the New York meeting, February, 1932, and published by the American Institute of Mining and Metallurgical Engineers as Technical Publication No. 483, Class L, Geophysical Prospecting, No. 37.

QUENTIN D. SINGEWALD, University of Rochester, Rochester, New York, has a paper entitled "Igneous History of the Buckskin Gulch Stock, Colorado," in the *American Journal of Science* for July, 1932.

E. O. ULRICH, M. R. CAMPBELL, and F. C. SCHRADER, geologists of the U. S. Geological Survey, were retired, June 30, in accordance with the provisions of the Economy Appropriation Bill recently enacted by Congress and approved by the President.

The Shreveport Geological Society has on hand copies of a 14-page printed pamphlet on the itinerary of the society's ninth annual field trip (June, 1932), including a map of southeastern Mississippi and southwestern Alabama, a list of publications on the Tertiary geology of the two states, and a correlation chart. Copies may be obtained at $2.00 each, from Dugald Gordon, secretary-treasurer, 521 Slattery Building, Shreveport, Louisiana.

VAN H. MANNING died, July 13, at his home at Forest Hills, Queens, Long Island. He was 70 years old.

J. R. PEMBERTON, geologist, Los Angeles, was recently elected oil umpire for California.

MAX BORNHAUSER, geologist for the Superior Oil Company of California, has been transferred from Dallas to Houston, Texas.

LUIS E. KEMNITZER has returned from Germany after acting for more than two years as geologist for the Cities Service Company in that country. He will enter upon a period of private research at the California Institute of Technology, making the subject of his studies the geology and oil and gas resources of the islands off the coast of Southern California.

D. GLYNN JONES sailed from England, July 23, to accept a position for the Compania Terrocarrilera de Petroleo, Km. 8, Comodoro Rivadavia, R. Argentina, South America.

WESLEY G. GISH, representing the Sinclair-Prairie Oil Company, has moved from Tyler to Fort Worth, Texas.

WILLIAM M. BARRET, president of the geophysical firm of William M. Barret, Inc., is the author of an article appearing in the August 1 issue of the *Oil Weekly*, entitled "The Truth About the Magnetometer."

R. W. BYRAM is the Austin, Texas, correspondent for the *Oil Weekly*.

BRUCE L. CLARK, of the faculty of the University of California, Berkeley, is the author of "Age of Primary Faulting in the Coast Ranges of California," in *The Journal of Geology* of July-August, 1932.

P. L. DANA, recently with the geological department of the Gypsy Oil Company, may be addressed at Kewanee, Illinois.

JOSEPH JENSEN, chief petroleum engineer for the Associated Oil Company, presented a paper before the Los Angeles meeting of the A. I. M. E., July 28, which is published in the *Oil Weekly* of August 8 under the title, "Curtailment of Oil Production No New Thing in California."

P. S. HAURY has gone to Korea as metallurgist for Yeigu Mines, Ltd., at Heianhokudo.

LEW SUVERKROP, Bakersfield, California, consultant, has an article, "Orienting Drill Pipe with Surveyor's Transit," in the *Oil Weekly* of July 4.

ADDISON YOUNG, of Midland, Texas, is employed by the Landreth Production Corporation.

The Petroleum Division of the A. I. M. E. meets in Ponca City, Oklahoma, September 30 and October 1.

WINTHROP P. HAYNES is now located at 68 Pall Mall, London, S. W. 1, England, having transferred his office from Paris. He has general supervision of all geologic matters pertaining to the European subsidiaries of the Standard Oil Company of New Jersey.

A preliminary edition of the geologic map of Texas has been issued by the United States Geological Survey. The scale is 1: 500,000. Data are being collected for use on the final map.

THOMAS H. WILLIAMS has moved from Norman to Buffalo, Oklahoma.

CLEMENT A. WEINTZ, recently of Boulder, may now be addressed at Gearhart, via Orchard, Colorado.

W. G. ARGABRITE has moved from Chandler, Oklahoma, to Lewisburg, West Virginia, and is engaged in natural gas work.

WALTER J. BOYLE, recently located at Dodge City, is now at 731 South Spruce Street, Wichita, Kansas.

C. B. CLAYPOOL has been awarded a J. J. Storrow fellowship for 1932-33 in the Division of Geology and Geography of the National Research Council. His work will be in paleontology at the University of Illinois.

ROBERT H. DOTT has moved his office for consulting practice to 907 Atlas Life Building, Tulsa, Oklahoma.

Volume 16 Number 10

BULLETIN

of the

AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

OCTOBER 1932

GEOLOGY AND DEVELOPMENT OF OKLAHOMA CITY FIELD OKLAHOMA COUNTY, OKLAHOMA[1]

D. A. McGEE[2] and W. W. CLAWSON, JR.[3]
Oklahoma City, Oklahoma

ABSTRACT

The Oklahoma City field, located near the geographical center of the state, is a large faulted anticline in the pre-Pennsylvanian rocks the structure of which is represented by anticlinal folding in the Pennsylvanian and Permian sediments. It was discovered by geological mapping on the Garber sandstone (a surface formation). The main reservoir rocks are massive magnesian limestone of Cambro-Ordovician age and sandstones in the Simpson group of Ordovician age. Oil is obtained at depths ranging from 6,100 to 6,500 feet under pressures of 2,300 pounds per square inch. The total estimated productive area is 12,800 acres, approximately 60 per cent of which has been developed. Fifty-thousand-barrel wells are not uncommon. Many records have been established for the drilling and completion of large wells. Folding and faulting of the pre-Pennsylvanian sediments occurred in late Mississippian or early Pennsylvanian.

INTRODUCTION

The Oklahoma City field, located in T. 10, 11, and 12 N., R. 2 and 3 W., Oklahoma County, Oklahoma, ranks among the major oil fields of the Mid-Continent region. The depth of the producing formations and the extremely large volumes of gas and oil encountered under high pressures have developed new technique in drilling and production methods. The discovery of the field purely on geological evidence and

[1]Read before the Association at the Oklahoma City meeting, March 24, 1932. Manuscript received, May, 1932. C. R. Hoyle, E. I. Thompson and Norval Ballard of the Phillips Petroleum Company and L. R. McFarland of the Indian Territory Illuminating Oil Company actively assisted in the preparation of the paper.

[2]District geologist, Phillips Petroleum Company.

[3]District geologist, Indian Territory Illuminating Oil Company.

A preliminary edition of the geologic map of Texas has been issued by the United States Geological Survey. The scale is 1: 500,000. Data are being collected for use on the final map.

THOMAS H. WILLIAMS has moved from Norman to Buffalo, Oklahoma.

CLEMENT A. WEINTZ, recently of Boulder, may now be addressed at Gearhart, via Orchard, Colorado.

W. G. ARGABRITE has moved from Chandler, Oklahoma, to Lewisburg, West Virginia, and is engaged in natural gas work.

WALTER J. BOYLE, recently located at Dodge City, is now at 731 South Spruce Street, Wichita, Kansas.

C. B. CLAYPOOL has been awarded a J. J. Storrow fellowship for 1932-33 in the Division of Geology and Geography of the National Research Council. His work will be in paleontology at the University of Illinois.

ROBERT H. DOTT has moved his office for consulting practice to 907 Atlas Life Building, Tulsa, Oklahoma.